Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION UA®

FINAL REPORT ON
HAND-HELD ELECTRON BEAM GUN
AND EXTERNAL POWER SUPPLY

June 1965 - October 1966

G. S. Lawrence, F. R. Schollhammer

(Prepared under Contract NAS 9-4501 by the Hamilton Standard Division of United Aircraft Corporation, Windsor Locks, Connecticut, F. R. Schollhammer, et al).

FOREWORD

This Final Report covers the work performed under the National Aeronautics and Space Administration contract number NAS 9-4501 from June 1965 to October 1966.

This contract with the Hamilton Standard Division of United Aircraft Corporation, Windsor Locks, Connecticut is being administered by NASA Manned Spacecraft Center, General Research Procurement Branch, Houston, Texas under the technical direction of Mr. J. D. Medlock.

Mr. F. Richard Schollhammer of the Corporation's Hamilton Standard Division directs the program. Mr. Glen Lawrence supervises system development and Dr. Richard F. Donovan is the technical consultant.

This report has been reviewed and is approved.

John W. Meier

John W. Meier
Chief Engineer, Industrial Products Department

F. Richard Schollhammer

F. Richard Schollhammer
Program Manager

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Electron beam welding is a relatively new material joining technique which has many practical and useful applications including in-space welding. During the past few years this latter application has graduated from the concept stage to the laboratory, and now is finding serious consideration as the only practical means of providing in-space fabrication and maintenance.

Very simply, electron beam welding involves the bombardment of the workpiece to be joined with a finely-focused beam of high-speed electrons. Although the mass of an electron is very small, a stream of electrons at speeds near one-third the speed of light contains a significant amount of kinetic energy which is transformed into heat when the electrons strike the workpiece.

Electron beam welding is characterized by narrow fusion zones. This permits joining with significantly less heat input to the workpiece than with other types of fusion welding, resulting in less distortion and shrinkage as well as less power consumption, the latter being of extreme importance for in-space application. When carried out in a vacuum, it is an extremely pure process, permitting the joining of highly reactive metals and others sensitive to chemical contamination.

The Welding Research Council has concluded that,[(1)] "...common commercial welding techniques, such as the gas metal-arc or gas tungsten-arc processes, which require gaseous atmospheres, or submerged-arc or covered electrode welding, which are difficult to apply to thin materials and have not been developed for gravity-free, atmosphere-free use, will probably not be applicable to outer space environment welding". The solution to in-space welding thus lies in a true fusion process which exhibits minimal heat input, minimum fusion volume, and minimum demand on the available electrical energy.

The purpose of this program was to develop an electron beam welding gun capable of being eventually utilized for the fabrication and repair of vehicle components in evacuated man-rated space simulation chambers and as well as for the ultimate fabrication and repair of space-flight vehicles and components during actual missions. Electron beam systems normally operate in a vacuum atmosphere. Because of this and its high degree of efficiency, the basic welding concept is directly applicable to in-space welding of materials such as aluminum, titanium, and stainless steel.

The gun system developed in this program has been designed to be manually operated by a technician or an astronaut wearing a space suit. Design of the gun has been directed specifically towards considering the capabilities and limitations of a fully-suited astronaut. This involves such considerations as weight, size, shape, cable connections, control features, and radiation shielding. The gun is a hand-held, light-weight, variable-focus electron beam welding device. Hamilton Standard's proprietary ideas for a small electron beam gun, capable of operating in any atmosphere where the pressure

(1) Welding Journal, Vol. 41, No. 12, Welding Research Supplement 551-S, December 1962.

is less than $1x10^{-4}$ Torr, have been incorporated in the design of the gun. During this program, a hand-held gun was successfully operated and the required weldments were made in a man-rated space simulation chamber.

2.0 SUMMARY

Past and present studies have indicated that electron beam welding equipment is the best candidate for joining space-age materials in a high-vacuum environment. However, prior to the initiation of this program, electron beam welding equipment was heavy and not designed for space usage. The components used were bulky, particularly since a vacuum pumping system is required for use in the earth environment and also in part due to the voltage and power level requirements needed for deep-penetration welding of thick workpiece sections. In addition, earthbound electron beam welders also include several design features which although it makes them versatile tools for industrial uses, they then are extremely large and cumbersome for any intended space application. Since many of the above earthbound requirements are not needed for space welding, an electron beam welding system designed for space applications would have significantly less components and complexity than an earthbound system. Therefore, a program was conducted which had as its ultimate goal the demonstration of a hand-held electron beam welder in a simulated space environment. During this demonstration, in-space materials would be joined by the hand-held electron beam gun. Accordingly, this program consisted of three significant objectives:

a. the establishment of design criteria which could be used to define the electron optical column and the envelope of the gun;
b. the design and construction of an operable prototype hand-held electron beam gun which embodied the principles established in (a) above; and
c. the demonstration of the hand-held electron beam gun in (b) above under simulated space vacuum conditions using representative space materials and simple joint configurations.

The information embodied in this report summarizes the results obtained to complete these objectives.

During the initial study phase of this program, special attention was noted in the following areas:

a. providing a vapor-radiation shield around the immediate proximity of the weld area and still permit visual observation of the weld joint and/or weld process;
b. defining a handle for the gun which could be comfortably gripped and manipulated by a technician in a space suit;
c. moving the gun in a predetermined direction and at a uniform weld speed.

Prior to fabricating a prototype electron beam hand-held welder, a design study was made which included a definition of the type of electron optics and power (Watts) that would be required to weld typical aerospace materials of representative thicknesses. From previous studies it was determined that most of the in-space fabrication tasks would involve joining materials of approximately 0.075-inch thickness; a predominance of stainless steel, aluminum, or titanium alloys would be required for most of the common joint configurations (i.e. butt, lap, "T", etc.). The power required for the in-space hand-held welder to join these materials was determined from analytical investigations

and from earlier laboratory tests to be approximately 1 to 1.5 KW; at these powers an accelerating potential not to exceed 20 KV was deemed acceptable. These power and accelerating potential limits were established to provide an optimum gun size and weight and also create minimum radiation from the workpiece.

From the above studies, a breadboard electron beam welding concept was developed which eventually can make use of either available on-board power or a separate power pack. The breadboard and subsequently the prototype electron beam welder developed and fabricated measures 3.5 inches in diameter, 10 inches in length, and weighs less than 10 pounds (earth weight). To the hand-held welder, a cable of 50 feet in length connects the gun to a commercial-type power supply. The power supply and controls which furnish power to the welding gun has an output rating of 20 KV, 150 ma d.c. for electron beam accelerating voltage and current, a 20 V, 25 amp d.c. filament supply, and a self-biasing system. The power available from this power supply was more than the required 1.5 KW (at 20 KV) for the hand-held electron beam welder.

Prior to conducting the man-rated chamber tests, each major component of the electron beam gun was thoroughly evaluated by conducting systematic development tests. A detailed description of these tests and the results obtained are included in this report. After each component, such as the insulator, filament, magnetic lens, cable connection, and controls was successfully tested, these items were integrated, after which the operating capability of the complete gun assembly then was evaluated.

The weld penetration capabilities of the prototype gun were evaluated in a high-vacuum environment for various typical aerospace materials. A practical working distance for most welding applications was determined to be 1 to 4 inches beyond the exterior of the gun aperture. For the various materials investigated, penetration varied with welding speed and with beam power. However, at a maximum power of 15 KV and 100 ma (1.5 KW) and a weld speed of 15 ipm, penetrations of at least 0.125 inch were obtained in aluminum, titanium, and stainless steel. This performance was in excess of the contractual 0.075-inch requirement.

In addition to ascertaining the maximum penetration, representative sample specimens of butt and lap welds were made under high-vacuum conditions for the titanium and stainless steel aerospace materials. Optimum welding parameters were developed by evaluating the weld zone characteristics of the sample trial welds. The welding parameters included work distance, beam current, accelerating voltage, focus, and welding speed.

For the stainless steel test specimens, tensile tests were conducted. The ultimate and yield strengths of the stainless steel weldments were equal to or greater than the base metal. For the bend test weldments, the results of transverse bend tests indicated that no failures or incipient fractures occurred in the weld or weld zone.

For all materials investigated, the simulated in-space electron beam welds exhibited greater depth-to-width ratios and smaller grain sizes than those generally obtained in conventional fusion welds of similar specimens. The capability of fabricating welds having depth-to-width ratios of approximately ten is extremely important for in-space joining considerations, since the fusion area is a direct representation of the amount of energy and power required. It is therefore obvious that maximum weld efficiency and minimum in-space power requirements are afforded by electron beam welding.

Final demonstration of the hand-held electron beam welder was made in a man-rated space chamber. These tests were conducted for the purpose of:

a. demonstrating the reliability of a hand-held welding device;
b. demonstrating the safety of operation of such a device;
c. performing acceptable welds in a repeatable manner; and
d. suggesting new areas of development which could contribute to the further improvement of this special welding device.

3.0 DEVELOPMENT PROCEDURE

3.1 Development Schedule for Phases I and II

3.1.1 Phase I

The development schedule for Phase I of the program required the design and construction of a breadboard electron beam gun system to conduct the initial testing and evaluation of various electron optical parameters. The design data obtained from the breadboard gun was used to provide an improved gun design such that a preliminary electron beam gun model then could be fabricated. With the preliminary electron beam gun, more extensive testing could be conducted during Phase I. Specifically, the preliminary gun system was used for evaluating the penetration capability, work height distance, and beam spot size for the design eventually selected to be used in Phase II.

Included as part of the Phase I activity was the evaluation of the radiation shielding system and also minimizing the package envelope of system weight in accordance with the design objectives of the contract.

3.1.2 Phase II

The development schedule for Phase II required finalization of the preliminary gun design such that a prototype model could be fabricated and extensively tested prior to conducting tests in a man-rated space simulation chamber. Upon the manufacture and assembly of the prototype gun, the gun was tested initially in an auxiliary chamber for penetration, repeatability, radiation, electrostatic charging, and ease of operation.

The final portion of Phase II required testing the gun in a man-rated space chamber and completing several electron beam welds with the hand-held gun. During this final portion of Phase II, motion pictures of the process also were made.

The programs in both Phases I and II were carried out on schedule. Although some minor delays were encountered in some of the manufacturing and testing portions, other phases could be accelerated such that the complete program was completed in accordance with the contract schedule requirements.

3.2 Breadboard Gun - Basic Electron Optics

The electron optical portion of the preliminary gun design illustrated in Figure 1 consists principally of a Rogowski type of electron gun, which was selected because of its excellent performance in higher voltage commercial Hamilton Standard electron beam welding systems previously placed in operation. The cathode insulator mounting, filament support,

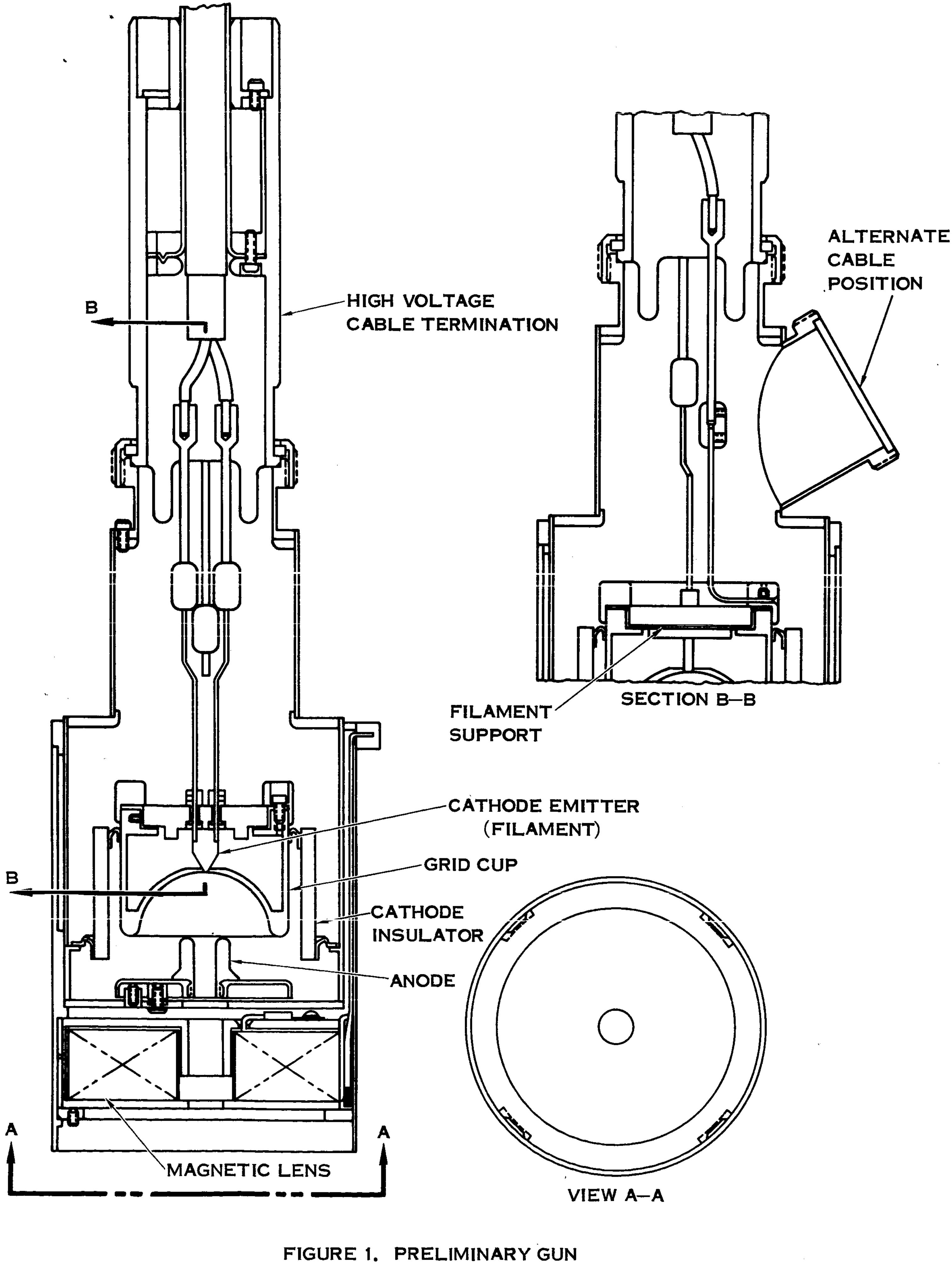


FIGURE 1. PRELIMINARY GUN

grid, and anode details and dimensions are somewhat different, but the basic configuration within the critical area of the emitter, grid, and anode is similar. Provisions were made for optimizing the size, configuration, and spacings between all three of the critical elements of the electron gun. The objective of the design was to achieve the performance capability required by the contract with parts that have minimum physical size and weight and have characteristics that are reliable and efficient in relation to the function performed.

The basic features of the preliminary gun are illustrated in the section view in Figure 1. Shown are the assembly of the gun components in the housing with the high voltage cable entering from the top for convenience in Phase I testing. The cable termination and the entire gun housing extends into the high vacuum inside a small test chamber adapted for this purpose (see Figure 2). The cable extended outside the high vacuum chamber to make connection to the power supply operating in a normal room ambient pressure and temperature.

The upper part of the electron gun housing includes a threaded fitting in two alternate locations for attachment of the high voltage cable termination. Although most of the testing in Phase I was done with the cable entering at the top as shown, some evaluation tests were conducted with the high voltage cable termination positioned in the alternate location on the side. The latter position simulated a proposed handle location on the final gun, entering at an angle of approximately 30° with the horizontal (see Figure 3). In both cases, the opening not being used as a cable entrance was utilized to insert the necessary tools to make the electrical interconnections between the cable termination and the electron gun.

The electron gun consists basically of a cathode emitter and a focusing grid, with the tip of the filament at the center of the gun. Vertical and horizontal adjustment of the filament with respect to the opening in the grid cup is provided. The grid cup, cathode insulator, and filament mounting constitutes one subassembly that is removable as a unit to permit bench-type servicing, such as filament replacement and adjustment or general cleaning of parts.

The anode is mounted on a separate base plate confined within the metal gun housing directly below the electron gun. Vertical and angular adjustments are provided to obtain the proper spacing and alignment with the grid cup. These adjustments and those mentioned previously for the filament mounting were necessary for the preliminary tests in order to take care of manufacturing tolerances and to provide means for varying critical spacings to obtain the best gun performance.

The magnetic lens coil is positioned under the anode base plate. The coil and its housing are separately removable from the overall gun housing assembly without disturbing the relative position of the anode and electron gun. This facilitates direct comparisons between the welding capabilities with and without magnetic focusing.

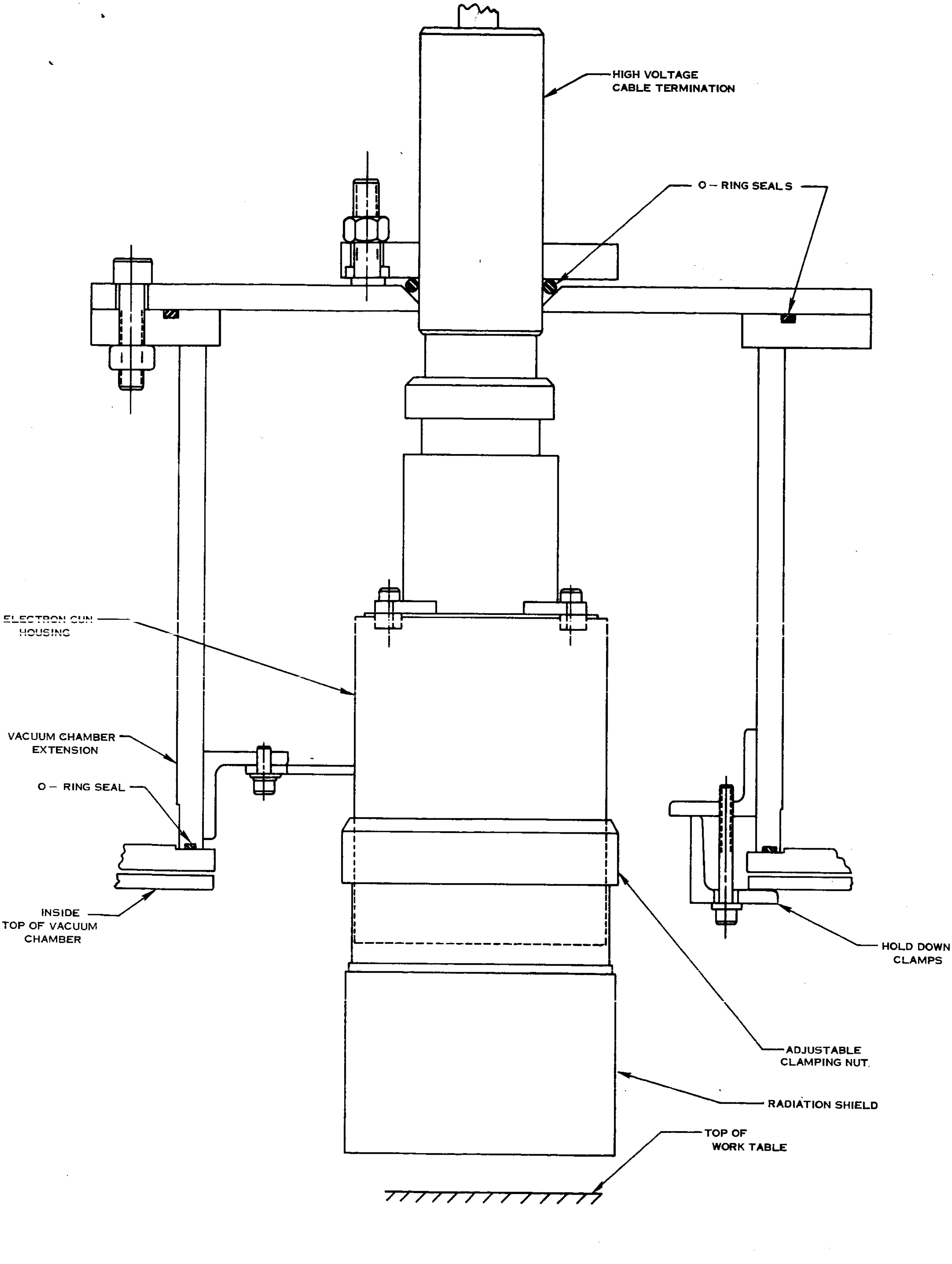


FIGURE 2. PRELIMINARY GUN ASSEMBLY FOR TEST.

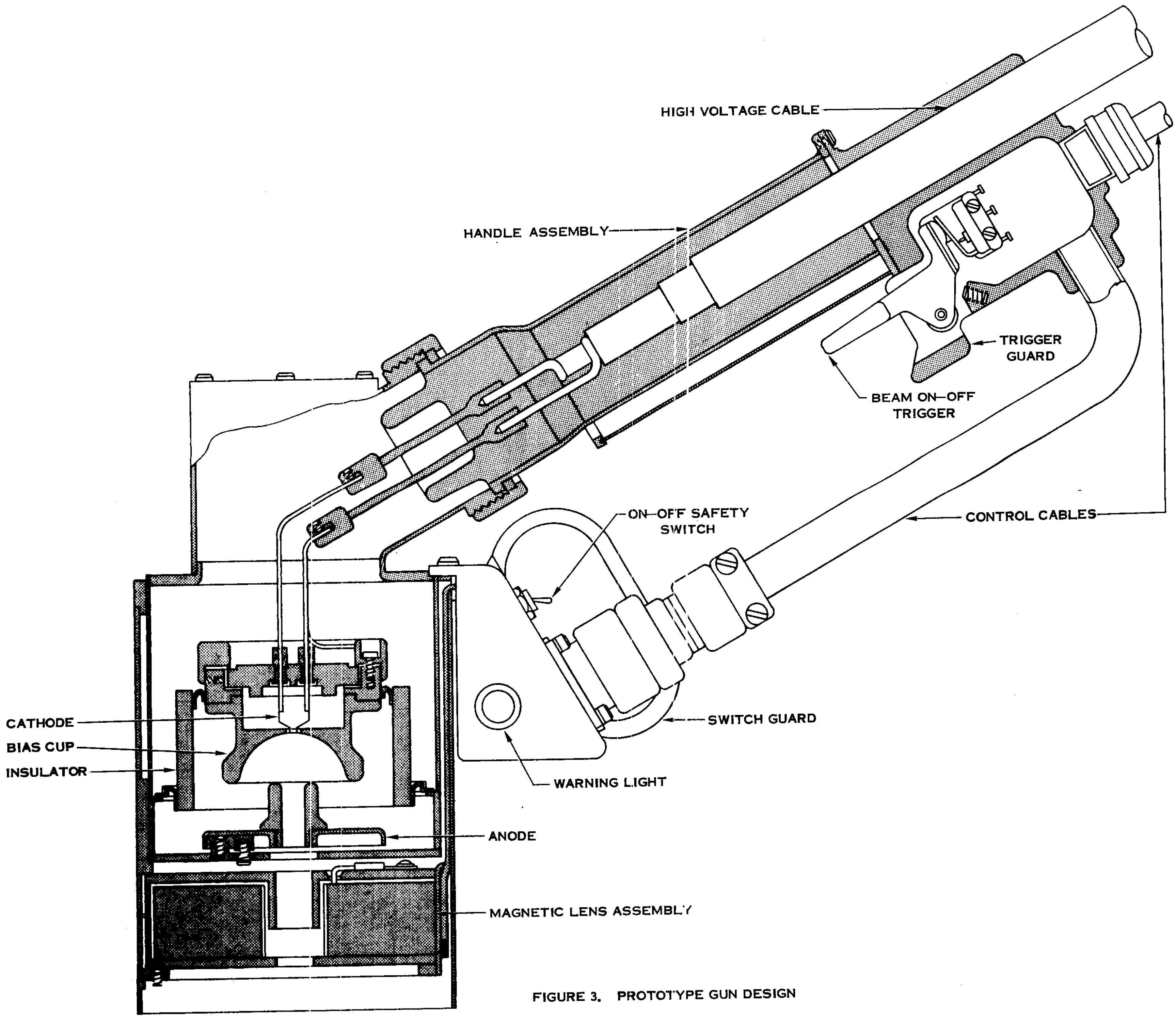


FIGURE 3. PROTOTYPE GUN DESIGN

Two basic classes of emitters were evaluated. One class included directly-heated filaments such as tungsten or tantalum. The second class includes small indirectly-heated cathodes capped with metallic impregnating compounds or mixtures which provide a highly efficient emitting source. Both types have inherent problems in use. Directly-heated cathodes consume more power than the indirectly-heated cathodes for the same electron emission, but the indirectly-heated cathodes are subject to "poisoning" when exposed to pressures exceeding the 10^{-4} range while hot. The emitter recommended for the final prototype model has taken into consideration availability, manufacturing, cost, power consumption, pressure effects, temperature effects, emission capability (in relation to accelerating voltage and power level), useful life and compatability with the balance of the system.

Test results indicated that there was no difficulty meeting the beam voltage and current output and weld penetration requirements. Further improvement of the beam spot size and adjustable control of the focal point location were accomplished with the use of a magnetic lens. The addition of the lens also permitted obtaining the required weld penetration at accelerating voltages less than 20 KV.

3.3 Prototype Gun - Phase II Model

The basic features of the prototype gun less the vapor-radiation shield are illustrated in the sectional view of Figure 3. This shows the assembly of the gun components in the housing with the high-voltage cable entering through the connector-handle assembly. The electron optical section of the gun is basically the same as the preliminary gun. The cable extends outside the high-vacuum chamber to make connection to the power supply operating in room ambient.

Several preliminary concept sketches were considered as a result of the Phase I preliminary gun studies. These were evaluated primarily from the standpoint of practical and economical fabrication requirements as well as in terms of the human engineering aspect of the man utilizing the gun in a space vacuum environment. Illustration of the finalized configuration is shown in Figure 4. This concept was used for guidance in the design of the prototype gun.

One problem that had to be considered further, for example, is the geometry of the handle, the angle at which it is attached to the housing, and the best configuration for an astronaut in a gloved condition, when holding the gun. The configuration selected is essentially a semielliptical tube which conforms to a shape suitable for the high-voltage cable termination, both electrically and mechanically. This design fits an astronaut's gloved hand to enable him to maneuver the gun in a space environment.

It should also be noted in Figure 4 that a low voltage control cable has been brought in separately. It has been looped together with the high voltage cable. At the end of the gun handle, the control cable passes through a grommet and is secured by means of a cable clamp. Wire

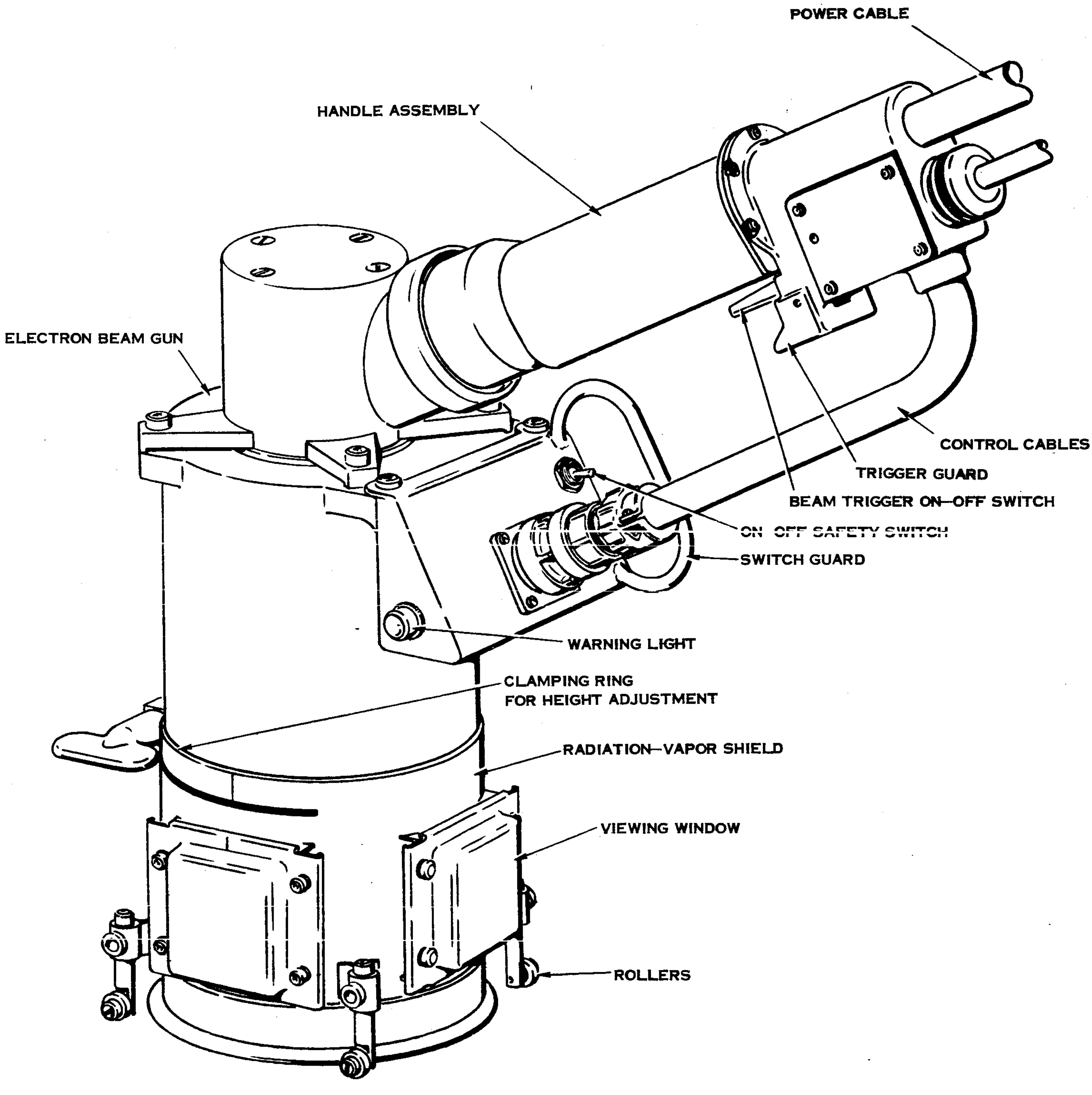


FIGURE 4. PROTOTYPE HAND—HELD ELECTRON BEAM GUN

conductors separate at this point and make connections to the gun trigger switch, the high voltage and reset switch, the warning light (indicates high-voltage power ON), and the magnetic lens coil inside the gun housing.

The radiation shield is cylindrical with rectangular bosses supporting a flat window of leaded glass on two adjacent sides down near the work surface (see Figure 4). This permits the operator to view the weld area; the shield also provides shielding from x-rays. The end of the gun is within this enclosed area and adjustment of the gun to work distance can be made by loosening the height adjusting clamp (attached to the radiation shield) and sliding the gun housing up or down as required, then retightening the clamp.

During the development program, it was decided that the type of bearing contact most suitable between the extremity of the radiation shield and the work surface is a series of four bearings - one located in each corner. The gap between the shield and work surface thus can be kept small to reduce radiation leakage. The direction of travel and the rate of speed is controllable by hand and the use of auxiliary fixtures.

3.4 Accessory Equipment

The accessory equipment includes primarily the radiation shield and viewing window assembly, all cables and connectors, feedthroughs, various control components, welding fixtures, and power supplies necessary to the operation of the gun. The design of the radiation shield and viewing window assembly is such that this assembly can be mounted or detached from the gun housing at will and also can be adjusted to various heights.

The prototype gun evaluation tests planned were conducted on a laboratory test stand. The high-vacuum chamber and column walls provide all the necessary x-ray shielding. Test fittings were designed and made available to conduct radiation measurements which verified calculated intensities.

The high-voltage cable consists of three center conductors and a high-voltage shield, supplying filament current and grid bias voltage to the electron gun. The major high-voltage insulation is extruded silicone, which is chosen for the relatively high-vacuum, high-temperature operating conditions and high radiation resistance. The ground shield is a woven mesh wire construction over the major insulation and this, in turn, is covered by a tough jacket. The gun end of the cable is stripped back as shown in Figure 3, secured in place within the metal handle assembly comprising the cable termination by means of a suitable epoxy potting compound. The other end of the cable, which connects to the high-voltage power supply (Figure 5), has a connector of similar construction and is shown in Figure 6.

The high-vacuum feedthrough for the cable was used for the prototype gun testing in the auxiliary chamber and for the man-rated space chamber tests. The design has proven to be vacuum leak-tight and serviceable. The feedthrough mounting plate, as seen in Figure 7, is circular and has the following pertinent dimensions:

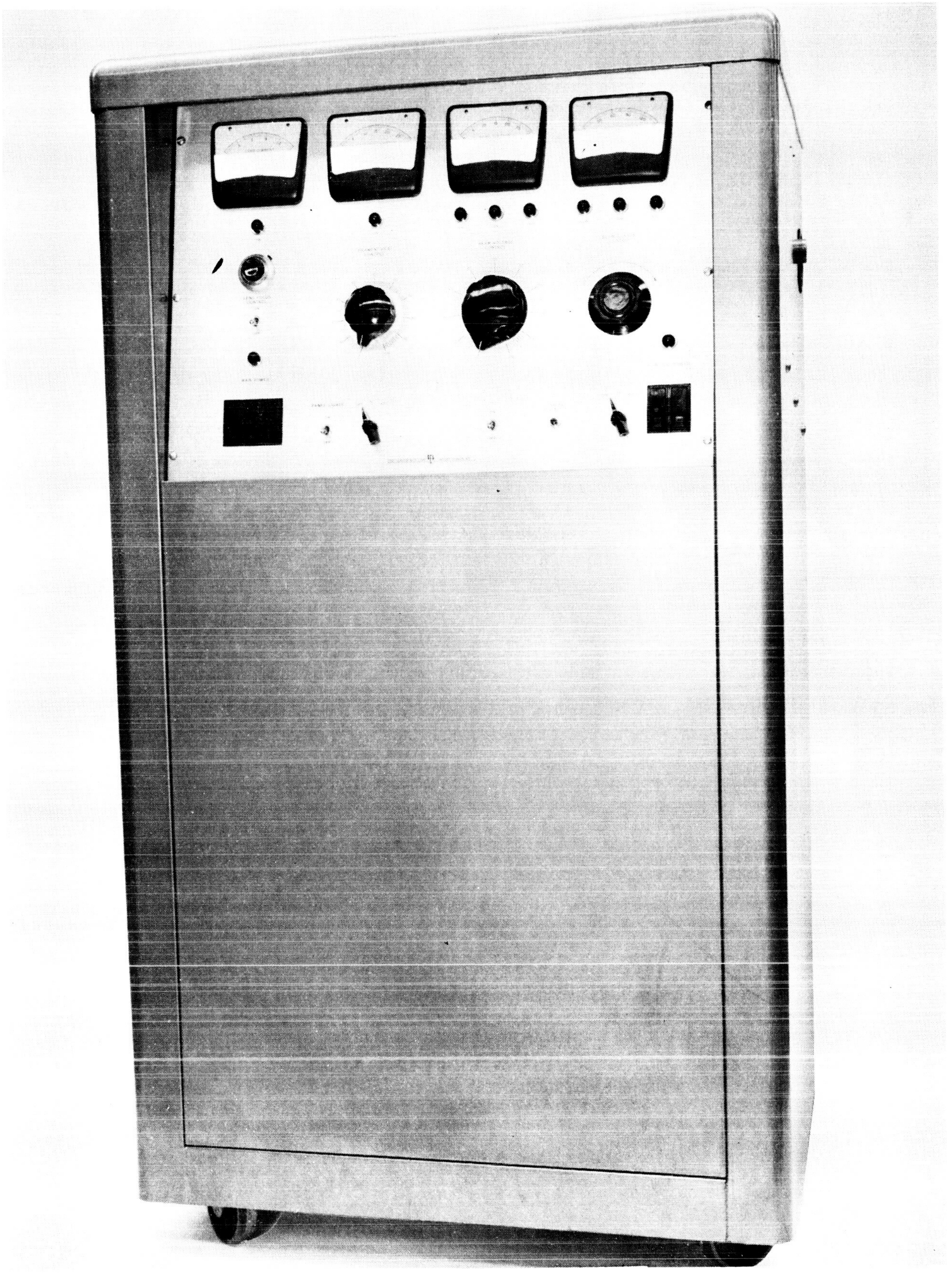


FIGURE 5. POWER SUPPLY FOR HAND HELD GUN

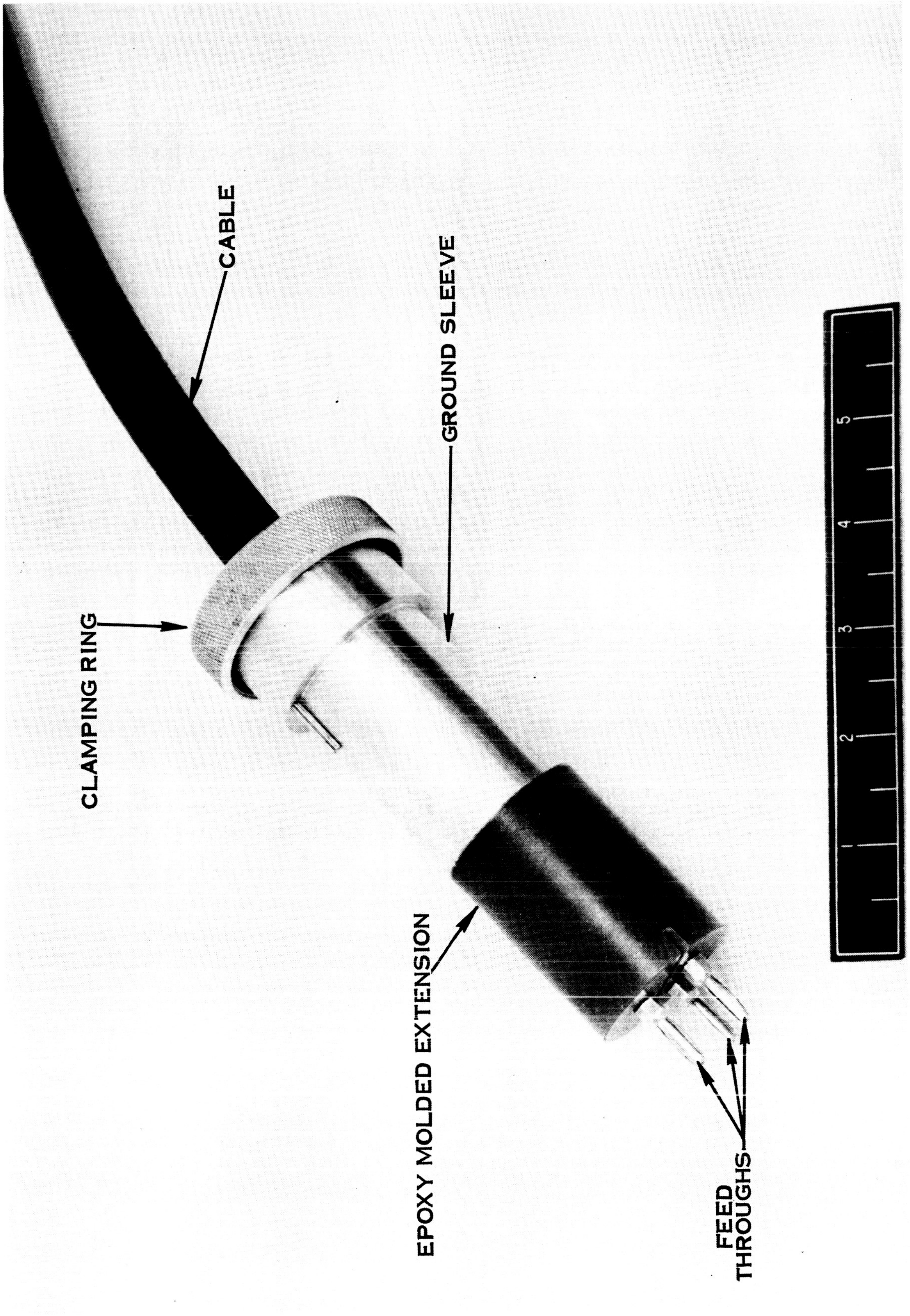


FIGURE 6. HIGH VOLTAGE TERMINATION TO POWER SUPPLY

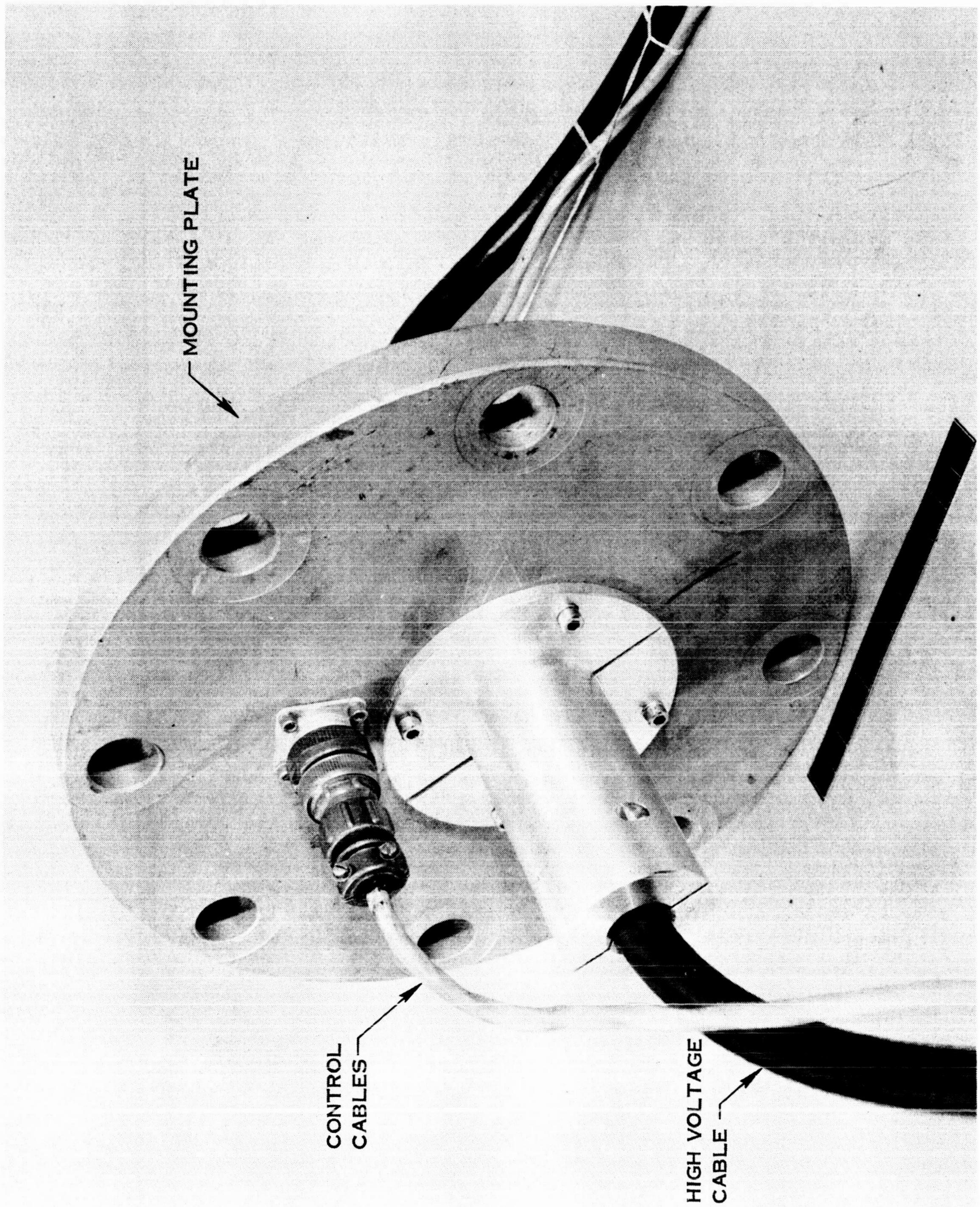


FIGURE 7. FEEDTHROUGH MOUNTING PLATE

Pipe Size	6 inches inside diameter, standard pipe
Flange Size	11 inches outside diameter, standard 150-pound fitting
Bolt Circle	9.5 inch diameter
Bolt Holes	0.875 inch diameter, 8 holes

The power supply and control panel for the prototype gun is shown in Figure 5. This has an output rating of 20 KV, 150 ma, d.c. for an electron beam accelerating voltage and current, a 20 volt, 25 amp d.c. filament supply and a self-biasing type bias supply. Power input is from a 3-phase, 220 volt line. The power requirements of the gun are well within the maximum capabilities of this equipment.

A workpiece fixture assembly, shown in Figure 8, was used with the electron beam gun for producing the first series of welds in the man-rated chamber. This fixture assembly was needed for several reasons, namely: (a) the fixture provided a receptacle for mounting and aligning the metal plates to be welded; (b) it assisted the test subject in moving the gun over a straight pattern; (c) it assisted the test subject in moving the gun to produce a smooth travel motion; (d) it minimized the possibility of inadvertently dropping or damaging the gun particularly during this first series of man-rated chamber tests; (e) it further eliminated the possibility of emitting x-radiation from the workpiece during welding; and (f) it provided an added protection against inadvertent exposure of the test subject's space suit to hot metal particles or electrostatic charging.

Although some or all of the above precautions and fixture assistance may not be necessary for future studies simulating in-space welding, the primary purpose of the initial tests was to evaluate hand-made electron beam welds. These provisions were considered necessary and appropriate by the safety and environmental health monitoring personnel.

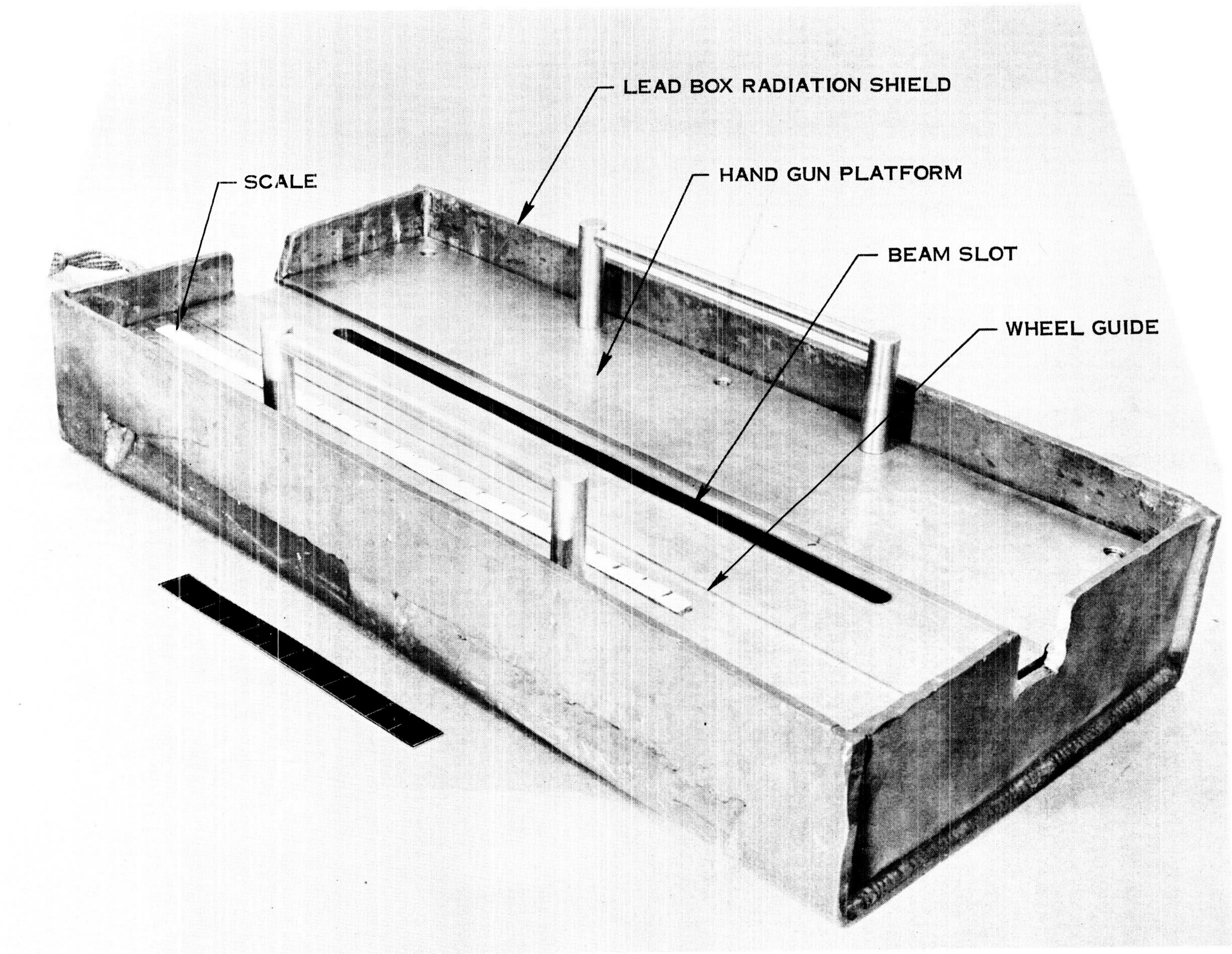


FIGURE 8. WORKPIECE FIXTURE ASSEMBLY

4.0 DEVELOPMENT TEST RESULTS

4.1 Electron Gun Evaluations

Initial tests to investigate the basic electron optical characteristics of the prototype electron gun were made using a full scale breadboard mock-up of the gun alone. Two different bias electrodes and anodes were designed so that four different guns could be assembled. Three of the four possible combinations were extensively tested. Initial tests led to the choice of three final configurations. They were identified as P-gun #1, P-gun #2, and P-gun #3 in order of increasing perveance. The guns were designed so that a 1.5 kilowatt beam could be obtained over a range of 12 KV to 20 KV beam potential. All three of the guns were operated at 1.5 KW with beam potentials less than 20 KV.

Weld penetration tests were made with each of the three guns. Typical penetrations, without the use of a magnetic focusing lens, are shown in Figure 9. All tests were made at a welding speed of 15 inches per minute. The material used in all cases was type 304 stainless steel.

P-gun #3 was selected for use in the prototype gun because of its high perveance, where perveance is defined as $K = \frac{I}{(V)^{3/2}}$. A high perveance is preferred because more current for a given voltage can be emitted. It has been operated at 1.5 KW at beam potentials as low as 12 KV. P-gun #3 also had more desirable basic electron optical characteristics.

4.2 Penetration Evaluations

Extensive penetration tests were run with the preliminary gun and also with the prototype gun. The data obtained from the penetration tests are shown in Figures 10 through 15.

In Figure 10, a comparison of the penetration obtained with the preliminary gun using two types of indirectly heated cathodes is shown. The workpiece material is 304 stainless steel; the welding was performed at 15 ipm. The penetration is essentially equivalent for the two cathodes.

In Figure 11, a comparison of the penetration obtained with the preliminary gun using tantalum ribbon filaments of different widths, and an indirectly heated cathode is shown. The workpiece material is 304 stainless steel; the welding was performed at 15 ipm. All emitters produced welds that satisfied the 0.075-inch penetration requirement stated in the contract. The penetration obtained with the indirectly heated cathode is better than the penetration obtained with the ribbon filament. The penetration with an indirectly heated cathode is maximum for a beam potential of 15 kilovolts, while the penetration obtained with the ribbon filament improves as the voltage is increased to 20 kilovolts. It also is noted that the penetration obtained with the smaller ribbon filament is better than the penetration obtained with the larger ribbon filament. It should be noted that the variation in penetration for the indirectly heated cathode in Figures 10 and 11 for the same power level can be

FIGURE 9

TYPICAL PRELIMINARY WELD PENETRATION TEST DATA - TYPE 304 STAINLESS STEEL

BEAM SETTING		MAXIMUM PENETRATION - INCHES		
Kilovolts	Milliamps	P-gun #1	P-gun #2	P-gun #3
15	54	.095	.132	.094
20	40	.096	.097	.093
20	75	.215	.135	.210
20	100	.198	.148	.270

NOTE: 1. Tests made without focusing lens.

2. Penetration runs were made on stacks of 0.125 inch thick blocks. Penetrations approaching or exceeding one block thickness would probably differ from penetration runs made in thicker material.

3. Welding speed in all cases -- 15 inches per minute.

FIGURE 10

COMPARISON OF PENETRATION FOR EXPERIMENTAL GUN USING INDIRECTLY HEATED CATHODES

Gun: P-gun #3
Table Speed: 15 ipm
Workpiece: 304 Stainless Steel
Focus: Magnetic Lens Focus at Workpiece

		Penetration in inches 4 inches from Gun				Penetration in inches 2 inches from Gun			
		Cathode No. 1		Cathode No. 2		Cathode No. 1		Cathode No. 2	
Beam Setting		Depth	Width	Depth	Width	Depth	Width	Depth	Width
15KV 54ma	800 watts	.088	.122	.085	.120	.130	.114	.225	.120
		.095	~~.[illegible]~~	~~.095~~	~~.120~~	~~.130~~	~~.122~~	~~.140~~	~~.102~~
20KV 40ma	800 watts	.142	.136	.120	.120	.190	.104	.180	.120
		.122	.136	.110	.110	.180	.106	.162	.122
12KV 65ma	800 watts	.100	.110	.080	.118	.160	.130	.174	.104
		.100	.110	.112	.124	.154	.140	.172	.105
15KV 100ma	1500 watts	.194	.180	.240	.180	.240	.156	.225	.182
		.200	.170	.160	.190	.320	.120	.221	.172
20KV 75ma	1500 watts	.165	.190	.202	.190	.202	.190	.228	.143
		.168	.170	.130	.196	----	----	.258	.150
12KV 125ma	1500 watts	.124	.160	.102	.150	.182	.164	.156	.150
		.130	.180	.100	.150	.160	.160	.142	.170

FIGURE 11

COMPARISON OF PENETRATION FOR PRELIMINARY GUN
USING RIBBON FILAMENTS AND INDIRECTLY HEATED CATHODE

Gun: P-gun #3
Table Speed: 15 ipm
Workpiece: 304 Stainless Steel
Focus: Magnetic Lens Focus at Workpiece

Beam Setting		Penetration in Inches 4 inches from Gun: Ribbon Filament No. 1		Ribbon Filament No. 2		Indirectly Heated Cathode		Penetration in Inches 2 inches from Gun: Ribbon Filament No. 1		Ribbon Filament No. 2		Indirectly Heated Cathode	
		Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width
15KV 54ma	800 watts	.068	.130	.095	.100	.100	.120	.075	.099	.120	.079	.160	.116
		.087	.134	.066	.110	.122	.124	.093	.097	----	----	.164	.118
20KV 40ma	800 watts	.085	.128	.106	.114	.122	.116	.106	.093	.114	.099	.140	.120
		.075	.083	.085	.108	.132	.110	.112	.093	----	----	.180	.100
12KV 65ma	800 watts	.066	.104	.037	.071	.180	.110	.065	.114	.056	.082	.188	.099
		.061	.160	.042	.077	.145	.120	.072	.116	.036	.080	.190	.100
15KV 100ma	1500 watts	.078	.190	.044	.084	.240	.164	.120	.130	.252	.150	.305	.120
		.102	.122	.070	.118	----	----	.120	.136	----	----	.150	.160
20KV 75ma	1500 watts	.098	.140	.152	.144	.200	.170	.136	.227	.243	.122	.182	.150
		.087	.194	.144	.148	.200	.180	.128	.170	.296	.089	.184	.150
12KV 125ma	1500 watts	.071	.112	.034	.060	.140	.150	.070	.094	.059	.095	----	----
		.073	.102	.050	.080	.140	.142	.088	.105	.058	.096	----	----

FIGURE 12

PENETRATION FOR PROTOTYPE GUN
USING INDIRECTLY HEATED CATHODE AND RIBBON FILAMENT NO. 2

Gun: P-gun #3
Table Speed: 15 ipm
Workpiece: 304 Stainless Steel
Focus: At Workpiece using Magnetic Lens

		Indirectly Heated Cathode				Ribbon Filament No. 2			
		Penetration in Inches				Penetration in Inches			
		4 in. from Gun		2 in. from Gun		4 in. from Gun		2 in. from Gun	
Beam Setting		Depth	Width	Depth	Width	Depth	Width	Depth	Width
15KV 54ma	800 watts	.126 .132	.124 .124	.178 .146	.112 .120	.174 ----	.106 ----	.102 ----	.124 ----
20KV 40ma	800 watts	.094 .090	.112 .096	.158 .132	.104 .125	.148 ----	.114 ----	.184 ----	.104 ----
12KV 65ma	800 watts	.172 .162	.122 .144	.209 .192	.087 .105	.055 ----	.095 ----	.128 ----	.106 ----
15KV 100ma	1500 watts	.267 .296	.138 .116	.282 .335	.132 .079	.134 .114	.168 .150	.178 ----	.180 ----
20KV 75ma	1500 watts	.194 .250	.166 .134	.290 .340	.120 .122	.295 .300	.144 .100	.310 ----	.079 ----
12KV 125ma	1500 watts	----	----	.185	.170	.106	.108	.100	.130

FIGURE 13

PENETRATION FOR PROTOTYPE GUN
IN 2219 ALUMINUM AND TITANIUM
USING INDIRECTLY HEATED CATHODE

Gun: P-gun #3
Table Speed: 15 ipm
Focus: Magnetic Lens Focus at Workpiece

Beam Setting	Penetration in Inches 4 inches from Electron Gun 2219 Aluminum Depth	Width	Titanium Depth	Width
15KV	.160	.225	.252	.114
100ma	.170	.430	.288	.256
20KV	.257	.235	.200	.160
75ma	.200	.400	.272	.268

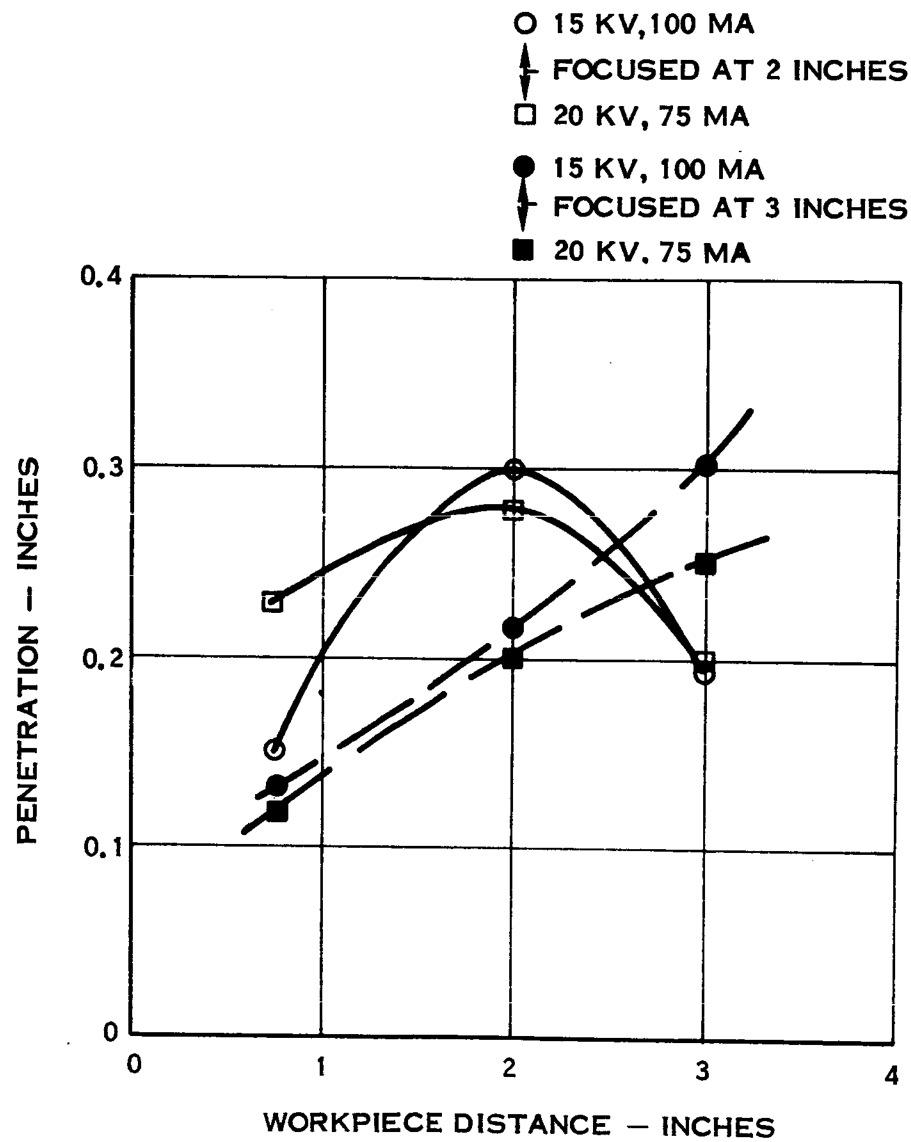


FIGURE 14 PENETRATION VS WORKING DISTANCE (AISI 304)

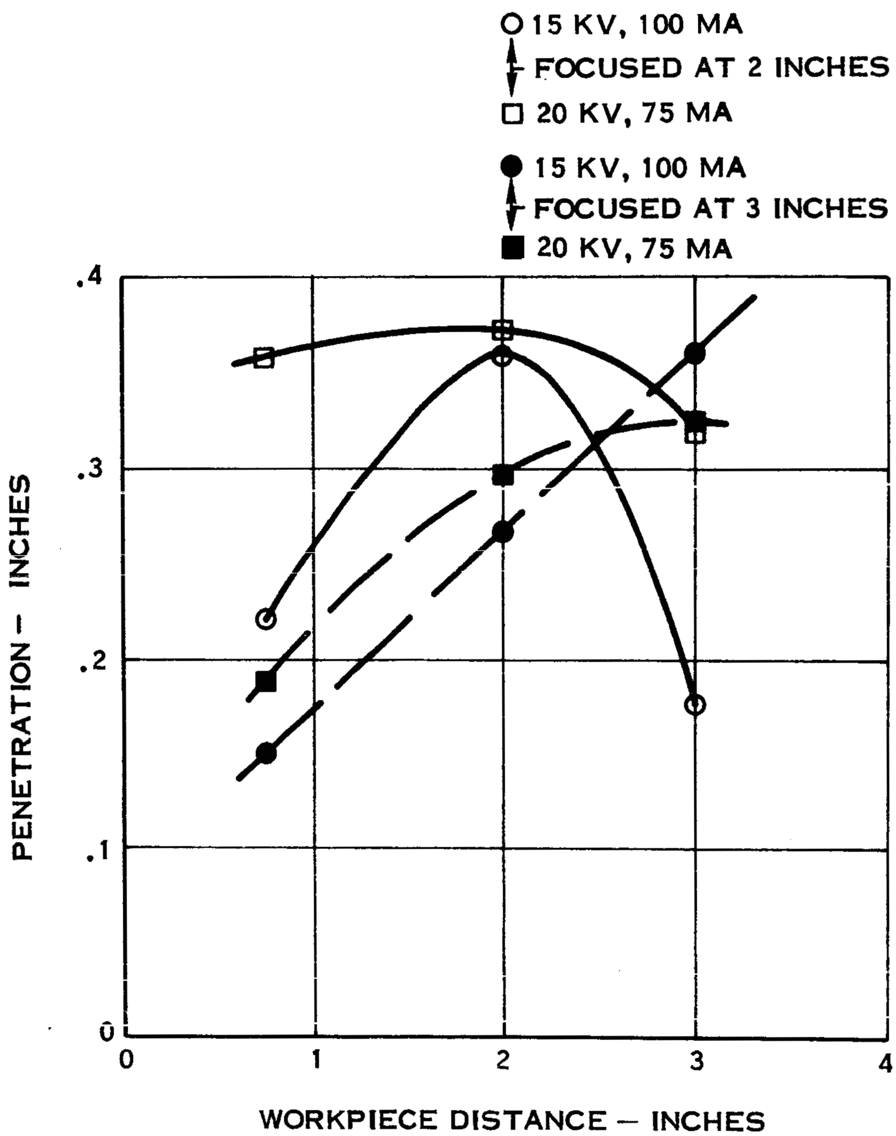


FIGURE 15 PENETRATION VS. WORKING DISTANCE (6–4 TITANIUM)

attributed to slight variations in the cathode-to-anode spacing as well as variations in focus.

Figure 12 shows the penetration obtained with the prototype gun using a thinner tantalum ribbon filament and the indirectly heated cathode. The workpiece material is 304 stainless steel; the welding was performed at a speed of 15 ipm. The data indicate that the penetration obtained with the prototype gun is equivalent to the penetration obtained with the preliminary gun.

Figure 13 shows the penetration obtained with the prototype gun when welding aluminum and titanium. These data were obtained to fulfill the contractual requirements. The indirectly heated cathode was used. The beam was operated at full power, that is, 1.5 KW, and the welding was performed at 15 ipm.

Figures 14 and 15 show the variation in penetration obtained for various workpiece distances with a fixed focal length. Workpiece materials included 304 stainless steel and titanium. Two focused lengths were used, three inches and two inches from the electron gun. These data were obtained to fulfill the contractual requirements.

4.3 Cathode Evaluations

General

Several different emitters were tested with the hand gun. Of the several different designs considered, two filament designs show the most promise. These are an indirectly heated cathode, and a tantalum ribbon (directly heated) filament.

The indirectly heated cathodes are composed of a pressed metallic slug approximately 3 mm in diameter. Heaters were bifilar-wound to reduce magnetic field effects.

The tantalum ribbon filament consists of a narrow strip of tantalum ribbon 5 mils thick. The ribbon is bent to form a square emitting area. Two different width filaments were used.

The cathodes were operated in a Veeco bell jar for calibration of temperature and life tests. Comparison of the data for the two types of filaments indicates that the ribbon filament requires almost three times as much power as the indirectly heated cathode. If resistance losses in the high voltage cable and connectors were included, the power consumption of the ribbon filament still would be greater - perhaps four or five times as much as that for the indirectly heated filament.

4.3.1 Heater Life

Initial testing with the indirectly heated cathode used tungsten heaters which were constructed in a bifilar-wound mode and ceramic-coated to provide electrical insulation. The heaters then were inserted into the cavity of the support cylinder to heat the cathode by radiation.

The lifetime experienced with these first heaters was poor. Maximum life under bell jar conditions was approximately two hours. It is postulated that failure was caused by degradation of the alumina coating since the mode of failure is usually due to an electrical short in the heater.

Several methods of increasing heater life were considered. However, the development of the indirectly-heated cathode from an experimental bell jar system to a working welder cathode has proven to be beyond the scope of this program.

Although directly-heated filaments were not preferred because of their high power consumption and the possibility of generating temperatures higher than desired within the gun, some testing also was conducted on these filaments. Tantalum ribbon filament No. 1 was life-tested in the bell jar. This filament lasted in excess of twenty hours. The temperature was 2050°C brightness as measured on the emitting face. This indicates that more than adequate life can be achieved from a directly-heated cathode.

4.3.2 Cathode Life

The usual problem with the indirectly heated cathode life of cathode No. 1 in a demountable system is poisoning when the system is vented and sensitivity to ion bombardment when the working pressure is too high. However, for cathode type two, these have not demonstrated any poisoning effects; these filaments also have demonstrated stable operation at pressures an order of magnitude higher than the usual cathode No. 1 design will tolerate.

Although the No. 2 indirectly-heated cathode has advantages over a ribbon heater in lower operating temperatures and less power consumption that are very important for a hand-held in-space gun, the factor of reliability is, at present, in favor of the ribbon filament. Based on the criteria of long life and high reliability and lower acceleration voltage operation, the larger tantalum ribbon filament designated as No. 1 has been selected for use in the hand gun.

4.4 Radiation Measurements and Shielding

A radiation hazard investigation was conducted as part of this program. Computations indicated that 0.031-inch minimum thickness of steel in the hand gun and radiation shield would adequately attenuate x-radiation at 20 KV to a safe level of less than 2 mR per hour. However, the study indicated that a strong x-ray emission pattern could be expected in the forward direction, that is, in the direction of the beam. Therefore, x-ray shielding should be provided on the reverse side of any weld being made. Including a safety factor, then this shielding should consist of approximately 0.040-inch of steel, or of a suitable material thickness having an equivalent absorption coefficient.

In order to confirm the various theoretical calculations of x-ray attenuation, radiation tests were performed with the hand gun in an experimental chamber. For radiation testing, a mylar window 0.003-inch thick was installed in the experimental chamber. A tungsten target, tilted towards the window, was then placed in the chamber, and the electron beam at various energies then was impinged upon the tungsten target. The radiation passing through the mylar window was monitored in ambient using a Victoreen S/N 214, Model 440, radio frequency-shielded radiation meter. Various thicknesses of shielding materials, particularly stainless steel, were placed in front of the mylar window, and the attenuated x-ray beam monitored. The results shown in Figure 16 indicate that the 0.040-inch thick steel shielding of the hand gun is adequate.

Various types of x-ray monitoring equipment were reviewed for monitoring radiation in a vacuum and at a relatively low accelerating potential of 15 to 20 KV. One of these, namely, photosensitive film, is recommended because of its ability to give spatial resultion of the radiation field, ability to serve well in a vacuum environment, and indicate sufficient sensitivity at 15 to 20 KV. This type of radiation monitoring was used during the manned chamber testing of the hand gun. The film badges are sensitive enough to register 1 milliroentgen at 15 kilovolts radiation. The test set-up prior to manned operation and during manned operation of the hand gun was monitored for x-ray radiation with these badges.

Radiation tests first were conducted in an auxiliary chamber to assure that the test subject would not be exposed to a radiation level that could exceed set safety standards. These tests were conducted with the vapor-radiation shield installed on the gun; the gun also was moved over the surface of the workpiece. This latter operation was deemed necessary and important to verify the soundness of the flexible shield used at the interface of the workpiece and the gun itself.

The tests were conducted over various intervals of welding time and at various welding speeds. The test conditions and results are tabulated in Figure 17 of time, speed, and results. No perceivable x-radiation was measured by either the Victoreen S/N 214, Model 440 or the film badges. The film badges contained two recording plates, a sensitive and an insensitive plate. The sensitive plates could record radiation as low as one milliroentgen; the insensitive plates could record radiation up to a total radiation dosage of fifteen roentgens.

During the man-rated chamber tests, fifteen radiation badges were located in strategic locations to monitor any possible radiation emitted by the electron beam gun. The location of the badges is shown in Figure 18. No radiation was measured by any of the badges located within the man-rated chamber including a badge mounted directly on top of the electron beam gun.

FIGURE 16

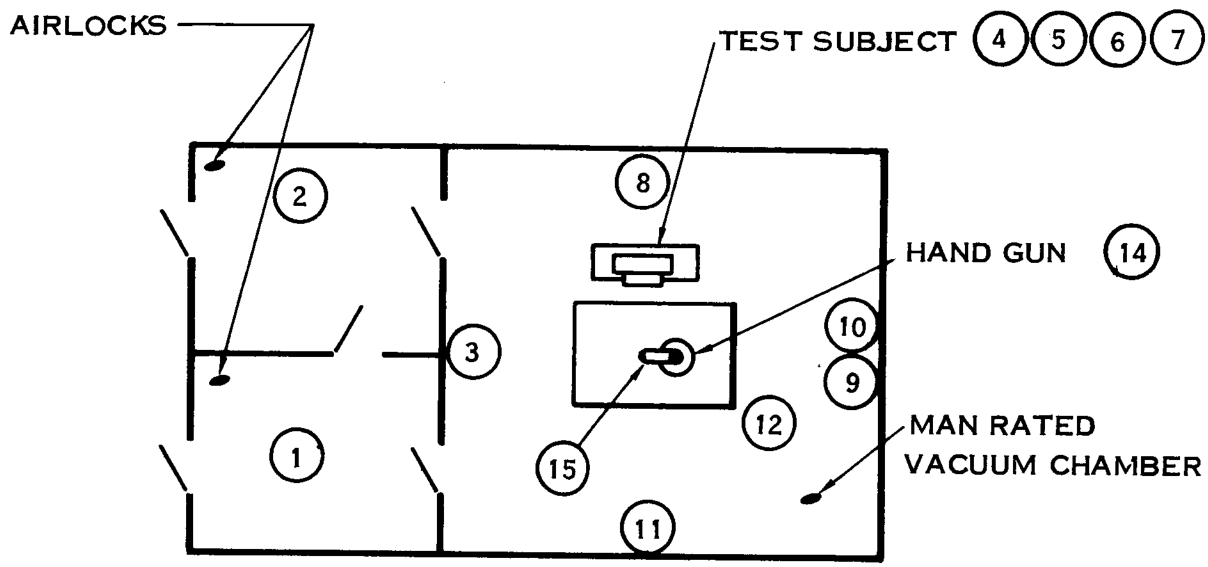
RADIATION TEST WITH 0.003-INCH THICK MYLAR WINDOW
USING VICTOREEN RADIATION METER S/N 214, MODEL 440, R.F. SHIELDED

	Measured Radiation in Milliroentgens per Hour				
Beam Setting	No Shielding	.008" S.S. Shield	.017" S.S. Shield	.025" S.S. Shield	.125" Aluminum Shield
12KV 0.2ma	> 300	---	---	---	---
12KV 60ma	---	.2	---	---	---
15KV 60ma	---	87	< .1	.05	---
15KV 100ma	---	90	.1	.1	---
20KV 75ma	---	---	---	3.6	---
20KV 100ma	---	---	---	7.2	---
15KV 75ma	---	---	---	---	1.8

FIGURE 17

RADIATION SHIELDING TEST SETTINGS

Badge No.	Distance from Source (inches) Horizontal	Vertical	Exposure
1	Control		
2	5 3/4	0	15KV, 100ma, 15 sec.
3	9 3/4	3	" " "
4	1 1/2	1 1/2	" " "
5	5 3/4	0	15KV, 100ma, 30 sec.
6	9 3/4	3	" " "
7	1 1/2	1 1/2	" " "
8	5 3/4	0	15KV, 100ma, 45 sec.
9	9 3/4	3	" " "
10	0	6	" " "



BADGE LOCATIONS

NO.	DISTANCE FROM SOURCE (FEET) HORIZONTAL	VERTICAL	
1	10	1 1/2	WORN BY LOCK ATTENDENTS
2	10	1 1/2	
3	5	2	
4	1	0	ABDOMEN
5	1	2	CHEST
6	1	2	CHEST
7	0	1/2	RIGHT HAND
8	6	1	
9	5	2	
10	5	2	
11	4	1 1/2	
12	1	1	
13	REFERENCE		
14	0	1/2	MOUNTED TO TOP OF GUN
15	0	−2	UNDER FIXTURE

FIGURE 18 FILM BADGE LOCATIONS MAN–RATED CHAMBER TESTS

4.5 Cable Potting and Connection Evaluation

There are four main considerations to be observed in the construction of the high voltage cable and terminations.

a. The cable has to be flexible and rugged to withstand repeated flexing without mechanical leakage.
b. The outer jacket of the cable must be vacuum leak-tight and have a low outgassing rate.
c. The vacuum feedthrough and in-vacuum termination of the cable must be vacuum leak-tight.
d. The cable and the termination assemblies must be capable of operating at 20 kilovolts under proper environmental conditions, i.e., with one end in vacuum and the other end in oil, half of the cable in vacuum and the other half of the cable at atmosphere.
e. The cable must withstand short periods of elevated transient temperature rise and be preferably radiation-resistant.

4.5.1 Cable Flexibility

The cable is constructed primarily from silicone to provide great flexibility. No damage, mechanical or electrical, to the cable assembly has been observed after repeated flexing during auxiliary chamber tests and during the man-rated chamber tests. The cable has been passed through a 6-inch pipe in coiled form (less than 3-inch bend radius) without difficulty or damage.

4.5.2 Cable Leak-tightness

The cable has helium leak-checked and no leakage through the outer jacket was found. With 25-feet of cable in a 5 cu. ft. chamber evacuated with a 4-inch diffusion pump and cold trap, the outgassing rate was low enough to permit a pressure of 5×10^{-5} Torr to be obtained. Attempts to measure the outgassing rate by using the rate of rise of pressure in the chamber were not very successful but did indicate that the rate must be less than 3 micron liters per second and probably less than one micron liter per second.

4.5.3 Cable Terminations

The cable terminations are potted with an epoxy compound using an anhydride hardener. The epoxy used has excellent electrical properties at temperatures up to 200°C (392°F).

The epoxy compound bonds to both the outer jacket of the cable and to the silicone cable insulation of the cable when the surfaces are properly prepared. The bonding is sufficient to produce both a vacuum-tight seal and an electrically-sound interface. Special potting techniques were developed to bond to the internal diameter of the metal housing for the termination and to prevent gas evolution from the silicone cable during the epoxy curing cycle.

One end of the cable is terminated in the handle assembly of the hand gun. This termination is designed to operate at high vacuum. The other end of the cable is terminated in an electrical connector that plugs into the high voltage power supply. This termination is designed to operate in oil. The cable is 50 feet long with 25 feet in vacuum and 25 feet in atmosphere.

The handle termination and the vacuum feedthrough are potted to the cable prior to potting the power supply termination. This permits the handle assembly to be helium leak-checked under high vacuum before the cable is sealed off by the power supply termination. No indication of leakage is permitted.

4.5.4 The cable is high voltage tested twice during its manufacture. It is initially tested after the handle assembly is potted. The handle is tested under high vacuum up to 22 kilovolts. After the power supply termination is fabricated, the cable is again tested with the handle in high vacuum and the power supply termination in 5 kilovolt steps of 5 minutes duration up to 20 kilovolts. The cable is then over-voltaged 10 percent for at least one minute.

4.6 Metallurgical Evaluations

General

Annealed AISI 304 stainless steel (hardness Rockwell B-88) was used for the sample test material. Electron beam weldments were made in material having a thickness of 0.075-inch. The tensile test coupons and also the bend test coupons were machined and then tested in the as-welded condition.

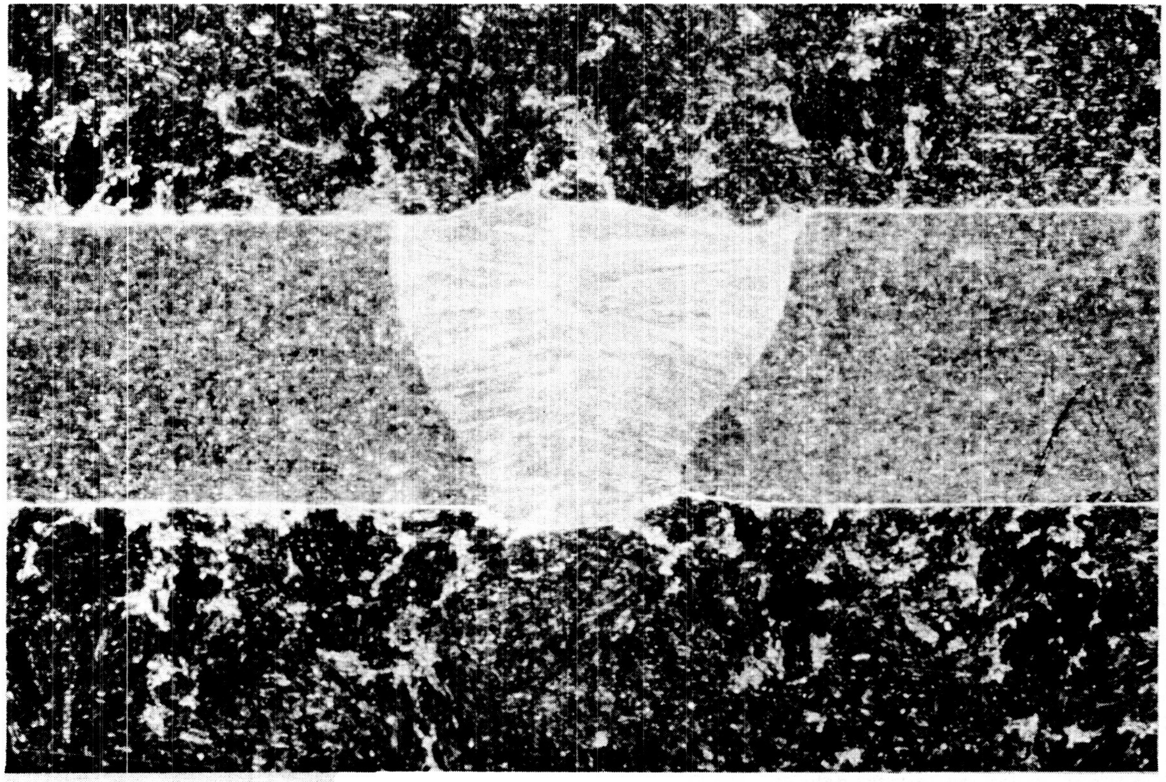
Nondestructive Tests

Visual examinations and radiographic inspections were made on all weld specimens. Inspection of the x-ray negatives and all weld joints indicated no apparent porosity. A typical weld fusion zone for a weld specimen is shown in Figure 19.

Destructive Tests

Tensile Tests: Welded tensile specimens were prepared to the dimensions shown in Figure 20. The machining direction was parallel to the direction of the applied force to insure that any effects upon the tensile properties due to machining would be the same for all specimens.

All welded and unwelded tensile specimens were tested at room temperature Each specimen was tested at a constant cross-head speed of 0.040 ipm to failure. During testing the specimen extension was recorded by an extensiometer and a plot of applied load force was automatically recorded. The ultimate tensile strength, yield strength at 0.2% offset, the percent elongation in 1 inch, and the location of fracture were determined from the test data.



POWER : 945 WATTS
SPEED : 36"/MIN

MATERIAL : 304SS
MAG. 20X

FIGURE 19. ELECTRON BEAM BUTT WELD

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

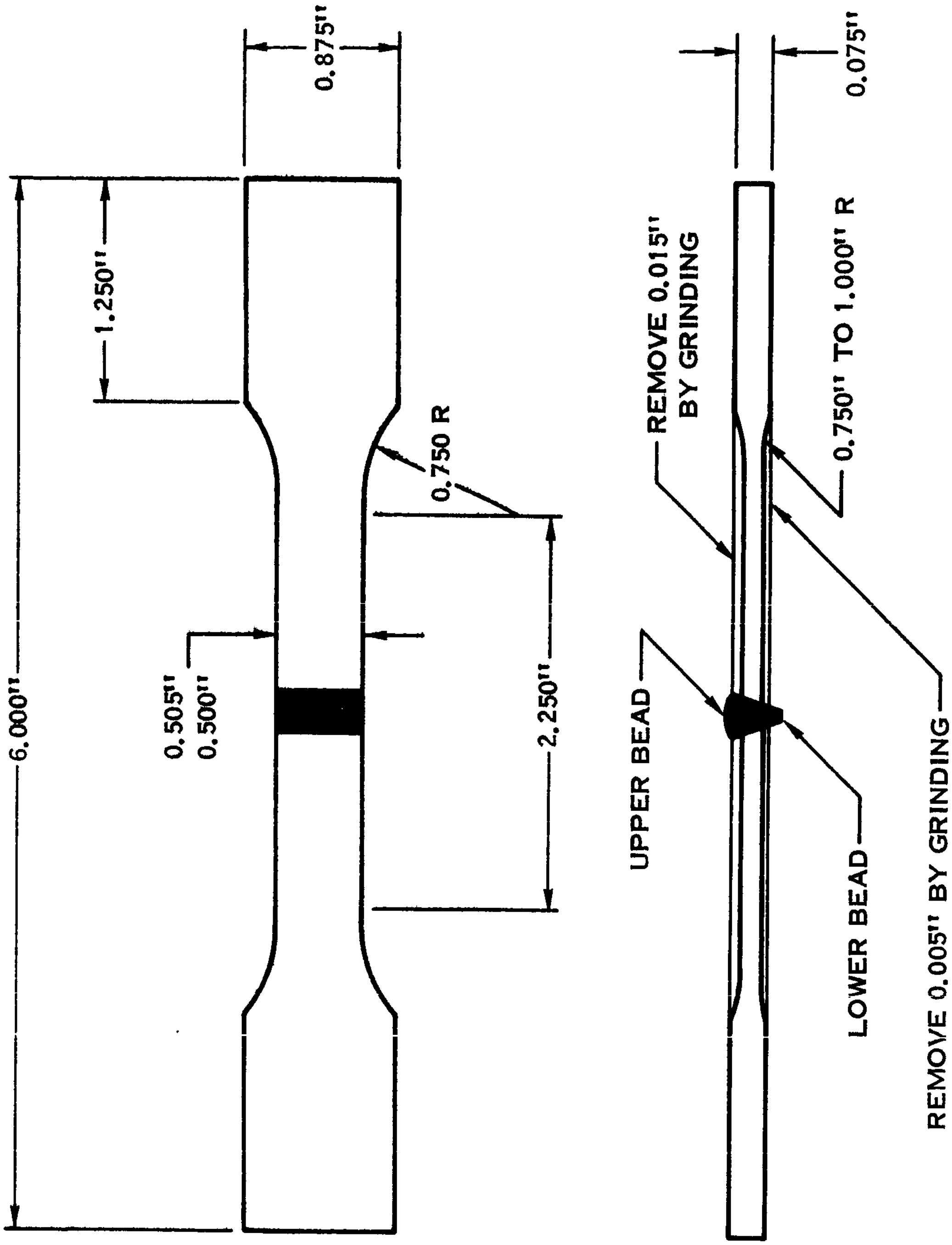


FIGURE 20 TENSILE TEST SPECIMEN (AISI 304)

The tensile test data for the eight 0.050-inch thick AISI 304 as-welded tensile specimens are listed in Figure 21. The data indicate that the tensile properties of the weldments were equal to or greater than the tensile properties of the unwelded base metal. All of the specimens except one failed in the weld zone; the remaining specimen failed in the base metal. Failure in the base metal was attributed to a local reduction in material thickness (approximately 0.001-inch) which occurred during final grinding and polishing operatons. Failure occurring in the weld zone can be attributed to two factors: (1) the tensile strength of the base material was higher than that of the weld zone, and (2) the weld zone width was greater than that normally found in high-voltage electron beam welds, but significantly narrower than those of other welding processes. Although all the failures except in one case occurred in the weld zone, the strength levels achieved were similar to those of the base metal. To account for the fracture occurrence in the weld zone it is known that: (1) the hardness of the weld zone was reduced to a VHN of approximately 190, as compared to base metal hardness of approximately VHN 200; (2) difference in grain size and shape occurred in the weld zone as compared to the base metal (Figure 22), and (3) reduced ductility in the weld zone may have resulted from the induced differences in grain size and shape.

The average yield strength value obtained for the specimens is 52,900 psi and the average ultimate strength value is 89,900 psi. The elongation for the specimens averaged 31%.

<u>Bend Tests</u>: Welded and unwelded bend specimens were prepared to the dimensions shown in Figure 23. Their rolling direction was parallel to the bending stresses. Approximately 0.012-inch of the material was removed from the top and bottom surfaces to insure that all discontinuities which could influence the test results were eliminated.

An installation consisting of a die secured to the movable crosshead of a tensile machine was used for testing these specimens. These bend dies are easily changed in the assembly to provide bend radius needed for tests. The bend specimen is placed in a female die; the span of this die can be adjusted as needed for the test requirement. A one-inch span was used for bend tests conducted at room temperature; the punch had a radius of 0.0625-inch.

Transverse bend tests were conducted on all specimens. This test method was chosen because the root or face of the weld is most likely to be poorly fused; thus, the maximum amount of weld area is subject to test. All specimens were bent until failure occurred or until the bending limit of the fixture was reached. Bending of the specimen was accomplished at a constant tensile machine crosshead speed of 0.050 ipm.

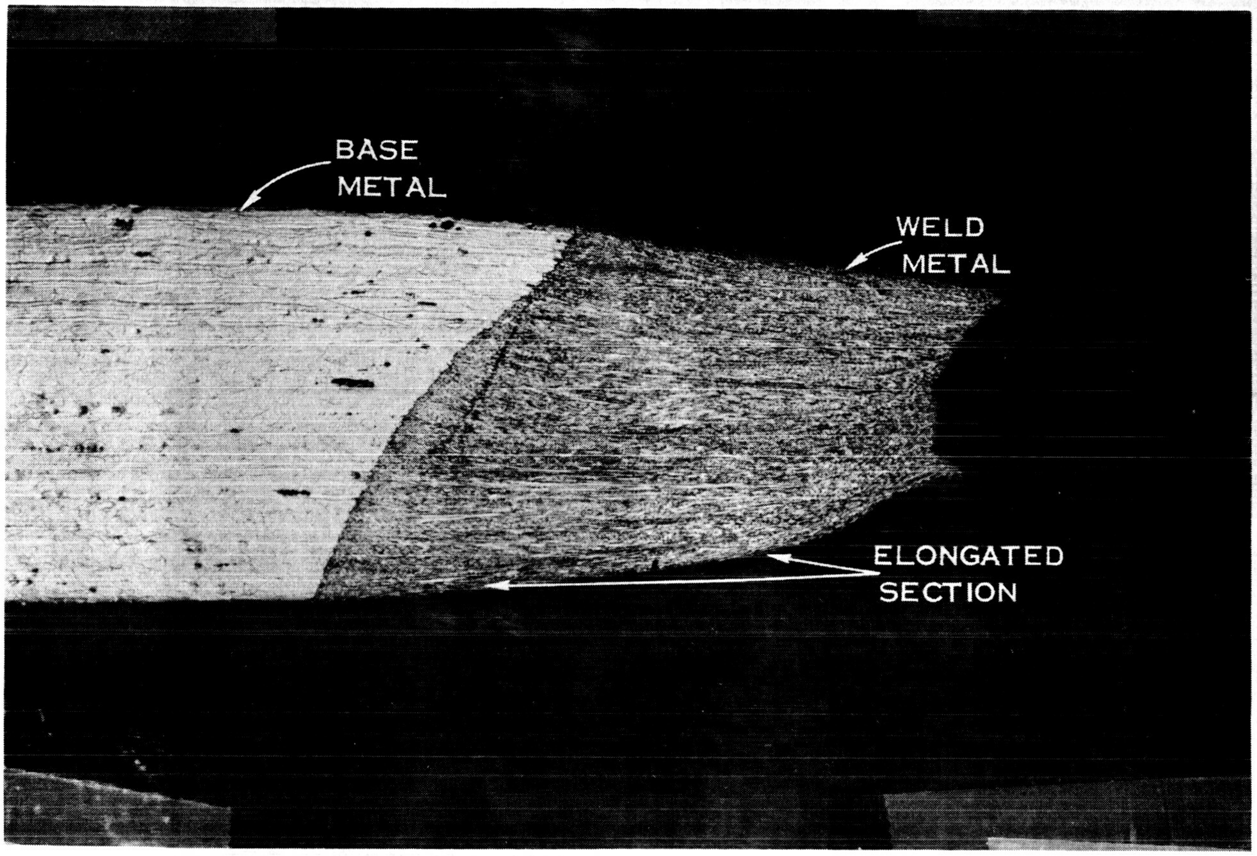
After testing, the permanent angle of bend was recorded. The angle of bend is defined as the angle at which the specimen was bent at the time of failure or until the bending limit of the fixture was reached, as measured after removal from the test equipment.

FIGURE 21

TENSILE PROPERTIES OF AISI 304 STAINLESS STEEL WELDS

Material	Thickness (inch)	Heat Treat Condition	Test Temp. (°F)	Ultimate Tensile Strength (psi)	Yield Strength at 0.2% Offset (psi)	Percent Elongation in 1 inch	Location of Failure	Radiographic Classification
AISI 304	.043	A, W	RT	98,576	54,762	31.5	W	O
"	.043	A, W	RT	87,429	55,714	23	"	"
"	.041	A, W	RT	86,700	57,400	31	"	"
"	.040	A, W	RT	86,000	50,500	30	"	"
"	.056	A, W	RT	85,358	47,680	21	"	"
"	.057	A, W	RT	92,142	54,250	32	"	"
"	.049	A, W	RT	86,000	47,800	29.5	"	"
"	.062	BM	RT	82,259	43,333	38		
"	.062	BM	RT	84,258	46,296	37		
"	.058	A, W	RT	78,824	46,138	42.5	BM	O

Legend:
O - No porosity
A - Annealed
W - Vacuum electron beam welded
RT - Room temperature
BM - Base metal
HAZ - Heat-affected zone



MAT'L AISI 304
MAG 15X

FIGURE 22. SPECIMEN AFTER TENSILE TEST

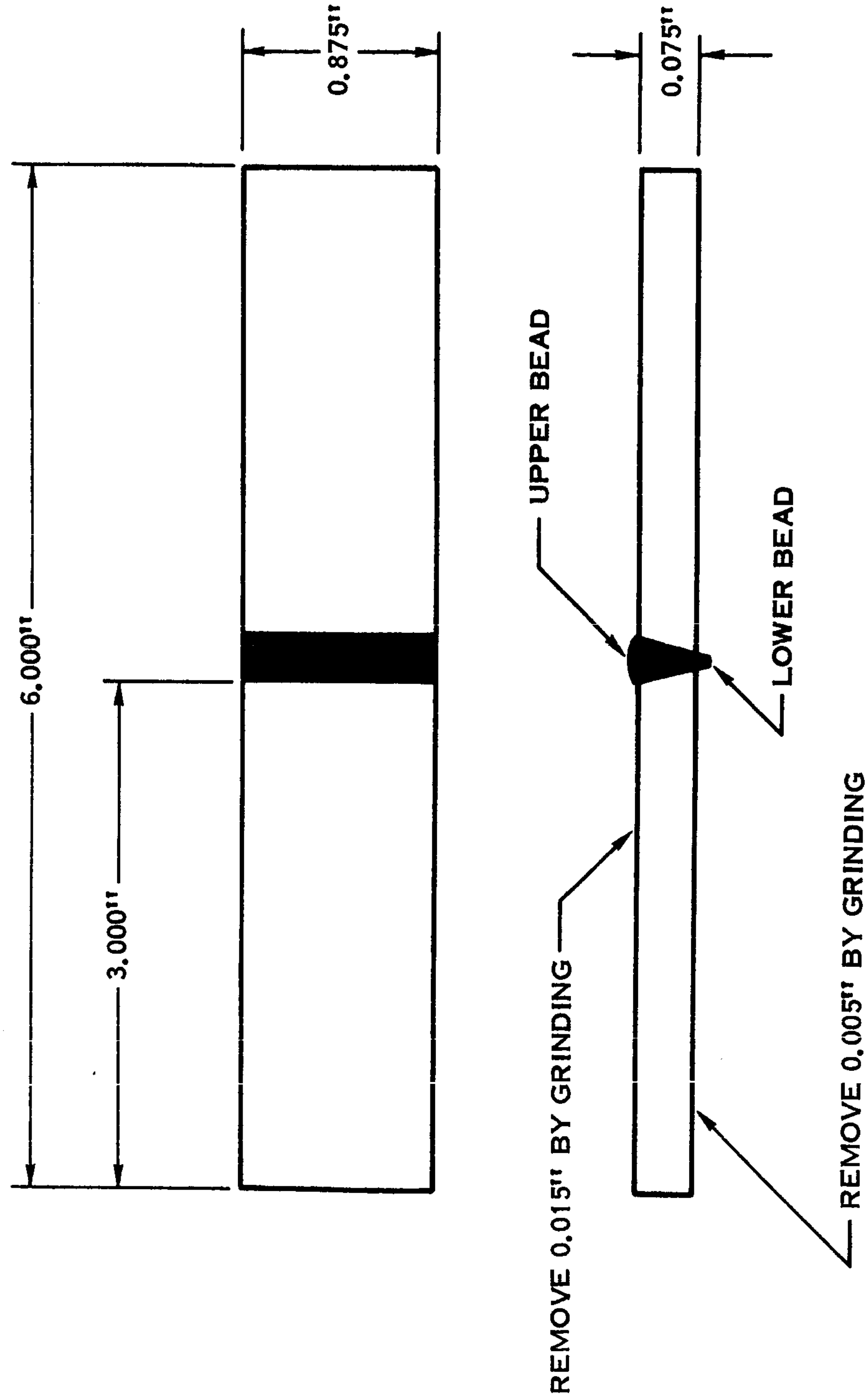


FIGURE 23 BEND TEST SPECIMEN (AISI 304)

The results of the bend tests are presented in Figure 24. As expected, the maximum ductility bend can be obtained for electron beam welds in the annealed condition. The bend ductility of the weld coupons approached that of the base metal. Visual inspection of all specimens indicated no incipient fractures in the weld zone.

4.7 Prototype Gun Tests

The testing of the prototype gun consisted primarily of the man-rated chamber tests. Preliminary testing of the gun was carried out, however, to insure the safety of the operator and the equipment. These tests included the following:

a. X-radiation tests were conducted throughout the testing program including the man-rated chamber tests to insure personnel safety (reference Section 4.4).
b. Temperature tests were carried out on the handle assembly to assure no over heating of the epoxy potting would occur.
c. Electrostatic tests were conducted to determine if electrostatic charge was contained by the gun shielding.
d. Auxiliary chamber tests were run to checkout the operation of the assembled prototype gun and the operation of the vapor-radiation shield.
e. The man-rated chamber tests were performed to demonstrate the operational ability of the hand gun and feasibility of producing welds by hand in a high vacuum environment.

4.7.1 Temperature Tests - Gun Handle

The epoxy-molded section at the inlet or forward section of the gun handle was instrumented with an iron-constantan thermocouple on the filament conductor and a copper-constantan thermocouple on the handle surface. The purpose of these tests was to determine the degree of heat transfer from the filament to the epoxy or potted region of the handle assembly. These tests were conducted with an indirectly-heated filament and also with a directly-heated filament (tantalum ribbon). The indirectly-heated filament required approximately 25 watts to product thermionic emission from the indirectly-heated compressed metal slug; the directly-heated filament requires considerably more heat, namely 125 watts to produce thermionic emission from the flat surface of the ribbon filament. The results of these tests are shown in Figures 25 and 26.

For the indirectly-heated filament, the temperature rose to 113°F in 30 minutes while for the directly heated filament the temperature rose 298°F in 5 minutes. The heat is transferred to the handle region primarily by conduction through the tantalum connecting rods. Heat is generated by resistance heating in the connecting rods and junction. For the indirectly-heated filament, the temperature attained a maximum stable value of 116°F.

FIGURE 24

BEND TEST RESULTS OF AISI 304 STAINLESS STEEL WELDS

Material	Thickness (inch)	Heat Treat Condition	Test Temp. (°F)	Bend Span (inch)	Bend Radius (inch)	Angle of Bend (Degrees)	Location of Failure	Radiographic Classification
AISI 304	.053	A, W	RT	1	.0625	180	None	O
"	.057	A, W	RT	1	"	"	"	"
"	.054	A, W	RT	1	"	"	"	"
"	.056	A, W	RT	1	"	"	"	"
"	.058	A, W	RT	1	"	"	"	"
"	.050	A, W	RT	1	"	"	"	"
"	.059	A, W	RT	1	"	"	"	"
"	.057	A, W	RT	1	"	"	"	"
"	.054	A, W	RT	1	"	"	"	"
"	.053	A, W	RT	1	"	"	"	"
"	.062	A, BM	RT	1	"	"	"	"
"	.062	A, BM	RT	1	"	"	"	"

Legend:
O - No porosity
W - Vacuum electron beam welded
RT - Room temperature
T - Thickness of specimen
BM - Base metal
HAZ - Heat-affected zone
FZ - Fusion zone
A - Annealed

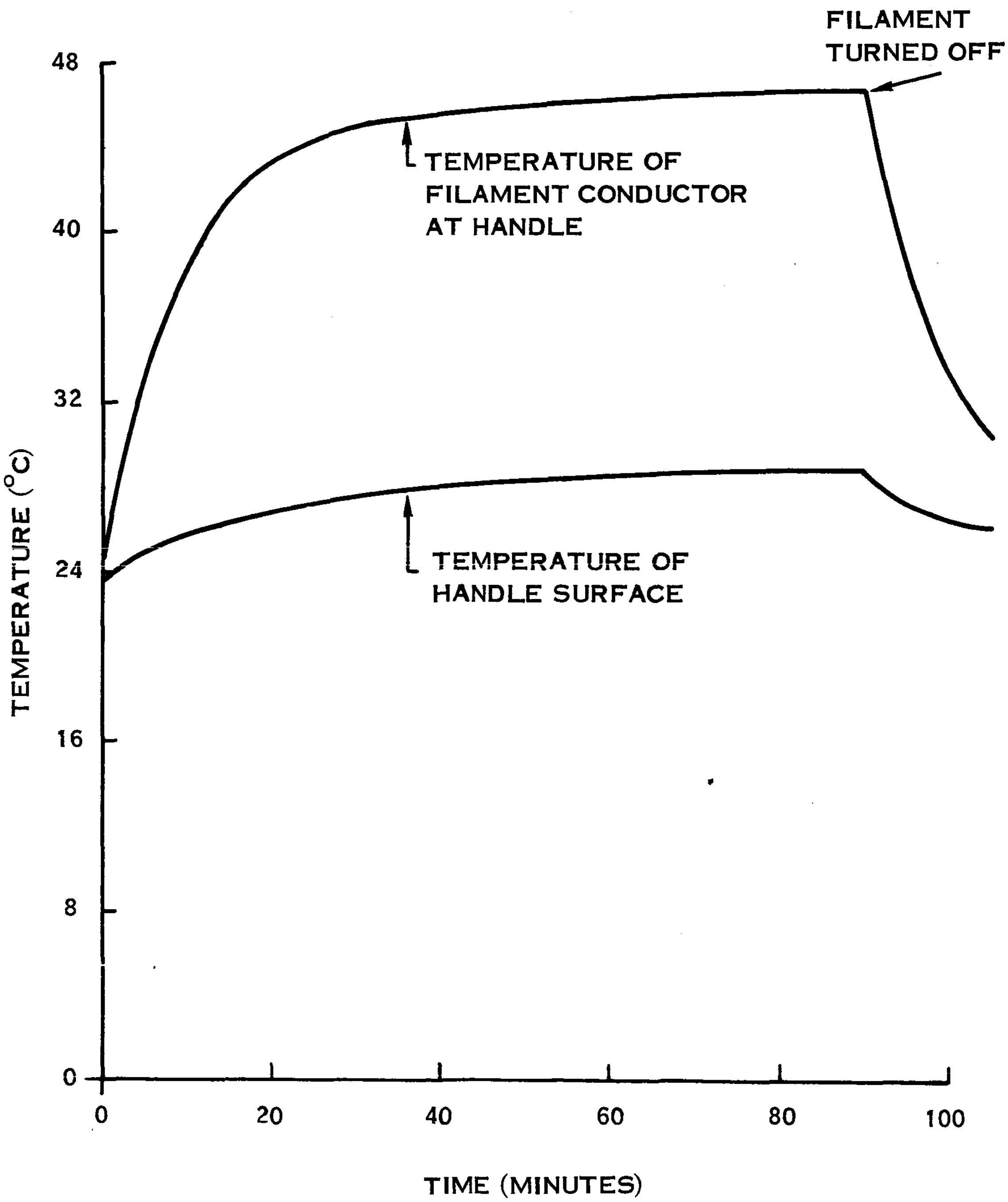


FIGURE 25. TEMPERATURE RISE OF HANDGUN HANDLE AT FILAMENT CONDUCTOR AND AT SURFACE USING INDIRECTLY HEATED CATHODE NO. 2

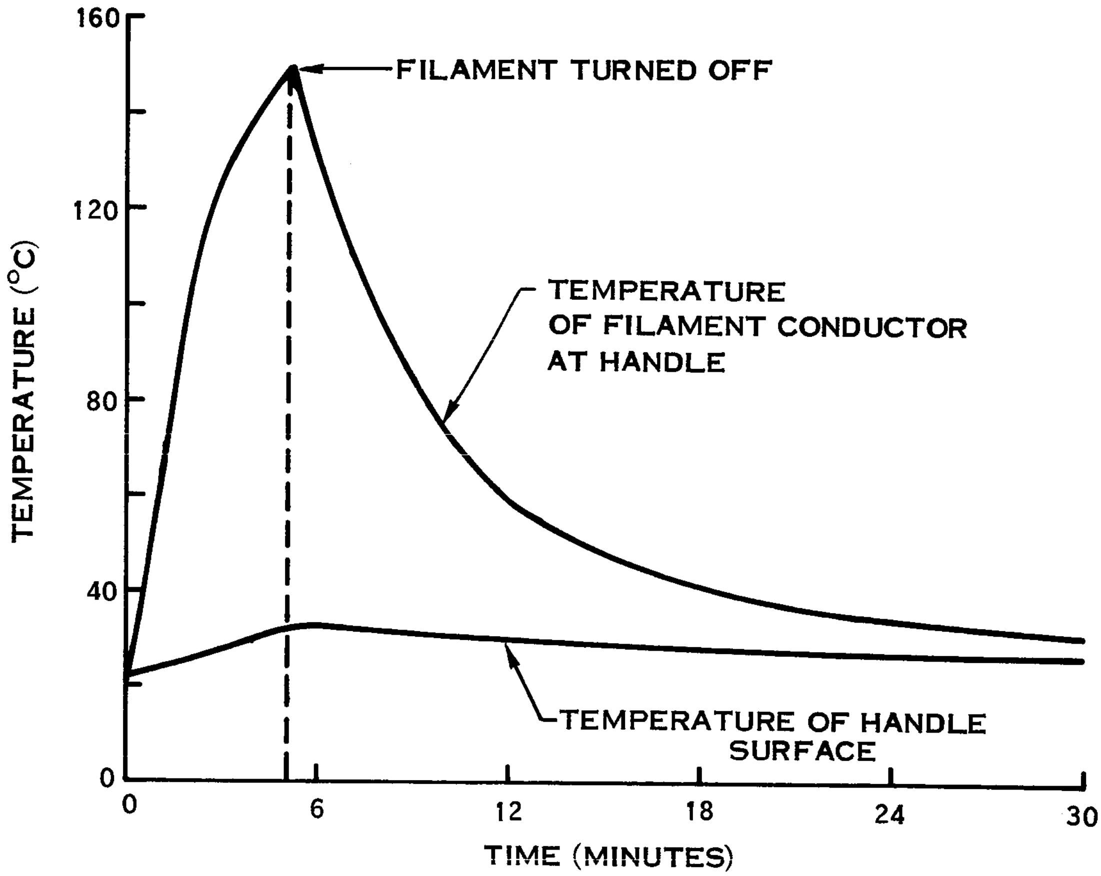


FIGURE 26. TEMPERATURE RISE OF HANDGUN HANDLE AT FILAMENT CONDUCTOR AND AT SURFACE USING RIBBON FILAMENT NO. 1

4.7.2 Electrostatic Tests

When an electron beam impinges on a target or workpiece, secondary emission occurs. In the release of this secondary emission, free electrons and ions are produced; most of these particles go to ground or are neutralized. In order to ascertain whether or not an electrostatic potential could exist on or around a space suit, several basic tests were conducted using a sample swatch of the outer exposure suit garment. This swatch was tufted with multiple nylon threads. Two or three tufts were tied together and bonded to the suit material at one common junction. Approximately thirty to forty junctions were used on the sample swatch. These number of tufts provided a sufficient tuft density for visual observation; the tufts were located on approximately one-inch square areas about every square inch.

Three series of tests were conducted. These were as follows:

a. The test piece was suspended from ground and located four inches from an unshielded beam.
b. The test piece was suspended from ground and located four inches from a shielded beam, i.e., the vapor-radiation shield was fastened to the gun as required for normal operation.
c. The test piece was grounded and located four inches from an unshielded beam, i.e. the vapor-radiation shield was omitted.

The results obtained from exposing the tufted garment to a maximum beam power (1.5 KW) for periods of ten to forty seconds were as follows:

a. With the garment suspended and exposed to the beam and also to secondary emission, some charging of the tufts was observed.
b. With the garment suspended and exposed to a shielded beam, no electrostatic charging occurred, and
c. With the garment grounded, no electrostatic charging occurred.

The above tests confirm some of the similar work conducted at NASA-Houston.

For the man-rated chamber tests, the test subject and electron beam gun and workpiece were grounded. As an added precaution, the forearm of the test subject was instrumented with several nylon tufts in a manner similar to that used on the test material. During tests, these tufts were visually checked and again, as anticipated, no electrostatic charging of the space suit was observed.

4.7.3 Auxiliary Chamber Tests

Prior to conducting the actual man-rated chamber welding tests, the prototype model first was tested in an auxiliary chamber at various power levels up to the maximum rated power of 1500 watts. Initial test results indicated that some materials would outgas more than others particularly at the higher power levels. This outgassing created a significant pressure rise within the vapor-radiation shield, e.g., 10^{-5} to 10^{-2} Torr. This sudden increase of pressure within the vapor-radiation shield was of sufficient magnitude that arcing of the electron beam was observed. Whenever this electrical breakdown occurred, it was usually accompanied with tripping the power supply relays. This would then necessitate resetting the power supply controls for a continuation of the welding process.

To eliminate the arcing problem, the shield assembly was vented to prevent a pressure rise. The venting design was such that radiation emitted from the workpiece is still contained within the shield assembly. The design used on the prototype model proved to be acceptable as verified by tests. The beam could be sustained without arcover at maximum power and no perceivable radiation from the radiation shield could be measured (less than 1 milliroentgen). To prevent a similar problem when using the workpiece fixture assembly in the man-rated chamber, the workpiece fixture also was vented sufficiently to prevent a pressure rise. The venting was accomplished in a manner as to prevent a radiation leakage.

Before installing the equipment in the man-rated chamber, one other test in the auxiliary chamber was performed for the purpose of determining the maximum temperature rise of the workpiece when welding at 1500 watts. This was accomplished by instrumenting a representative sample weldment with thermocouples and measuring the temperature rise of the base metal. The thermocouples were located within one inch of the weld seam. At maximum power (1500 watts) and minimum weld speed (15 inches per minute), the temperature increased from an ambient of 75° to 105°F. This temperature rise occurred within three minutes after initial completion of the weld. Within an additional three to five minutes, the temperature decreased to near room temperature. This test indicated that no perceivable temperature would exist during any of the manual weld tests conducted in the man-rated chamber.

4.7.4 Man-rated Chamber Tests

The purpose of this test was to demonstrate that an electron beam gun is capable of being used for future fabrication and repair of space flight vehicles and components during actual missions as well as for fabrication and repair of these components in evacuated man-rated space simulation chambers. The gun tested is manually-operated by the test subject in a vacuum where the pressure was 2.6×10^{-5} Torr.

The tests were conducted in accordance with contractual requirements and a total of four, six-inch length weldments were made (Figure 27).

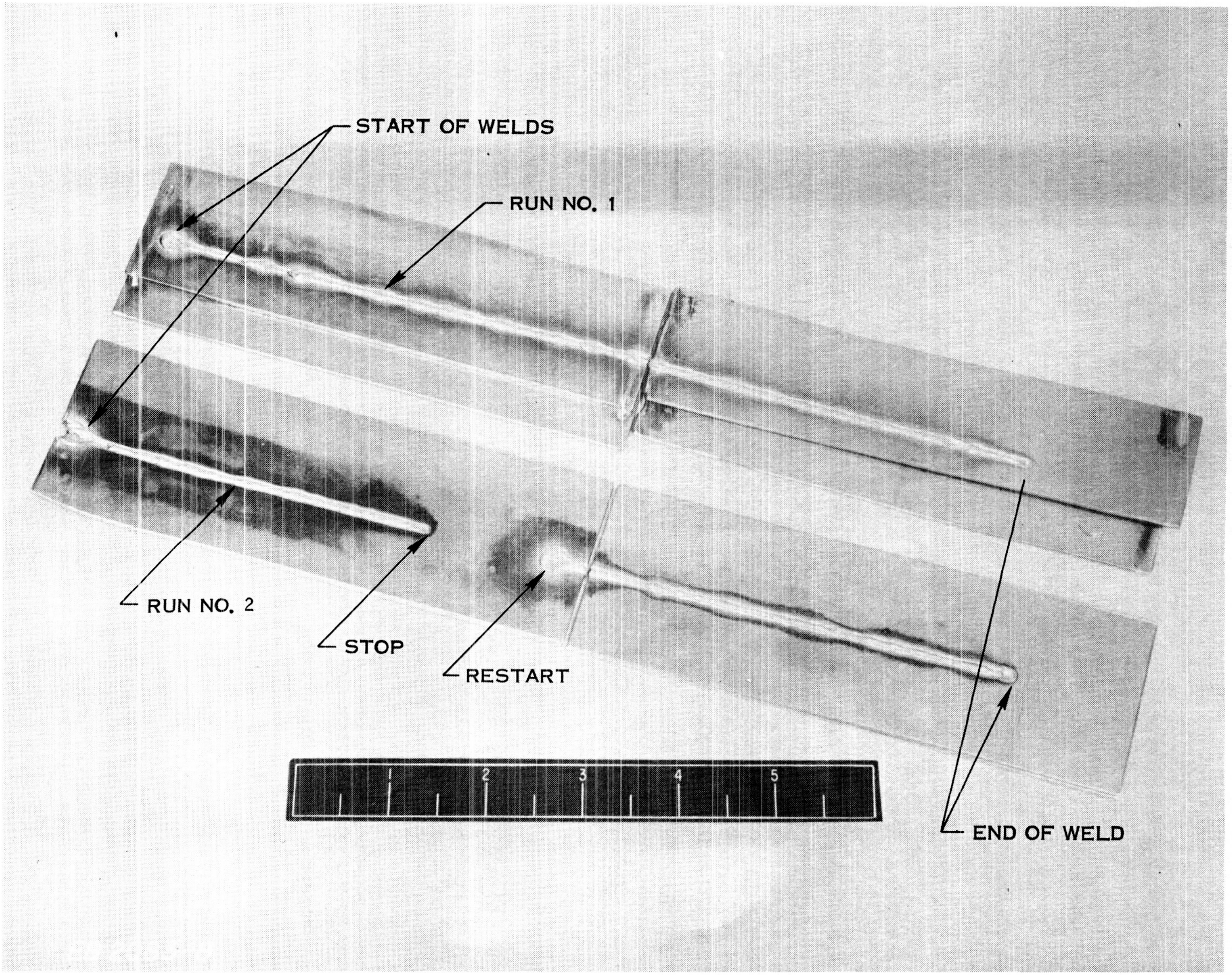


FIGURE 27. ELECTRON BEAM WELDS MADE BY HAND—HELD GUN

The results of the tests indicated efficiency and usefulness of a manual welding gun, and demonstrated the soundness of the electron beam gun design and the accompanying vapor-radiation shield. These chamber tests also defined some of the equipment handling problems such as ease of motion, gun handling, suit restrictions, etc., that could be encountered during high vacuum earth-bound operations. These problems now require further study by conducting additional space chamber tests.

Power to the electron beam gun was supplied from a conventional power supply located exterior of the chamber. The development of a compact supply capable of being operated in a vacuum was not part of the contract. Interconnections between the electron beam gun and the power supply were made by ducting a high voltage cable to the chamber wall. A special feedthrough penetration was designed to provide this cable feedthrough.

For welding a typical lap plate structure, the following steps were performed:

1. Locate the gun on the workpiece fixture assembly and move the gun to start position.
2. Adjust the voltage and beam current to appropriate values on the external power supply.
3. Move the toggle switch located on the gun to the ON position. The handle light, if lit, confirmed that the power supply has been turned on and that the gun now can be used for welding.
4. Depress the trigger switch located on the gun handle assembly to accomplish beam on or welding of the plate assembly.
5. Move the gun along the workpiece at approximate welding speed of thirty inches per minute.
6. Upon completing the full length of the weld, release the trigger and move the toggle switch to the OFF position.

Inspection of the welds was accomplished by removing a portion on the workpiece assembly fixture and loosening several Allen screws holding the workpiece to the weld fixture. The welds produced during these first manual test series are shown in Figure 27.

The quality and smoothness of the welds exceeded all expectations, especially for the first welds produced by the gun under manual operation since earlier laboratory mock-up tests had indicated that the manually-controlled speed of a free-wheeling device fluctuates grossly. A plot of the data is shown in Figure 28. A simple speed indicator consiting of a graduated scale was incorporated into the man-rated chamber tests to improve the control of the weld speed.

During the above welding operations, motion pictures of the process also were made. These pictures became part of the record and data of these tests.

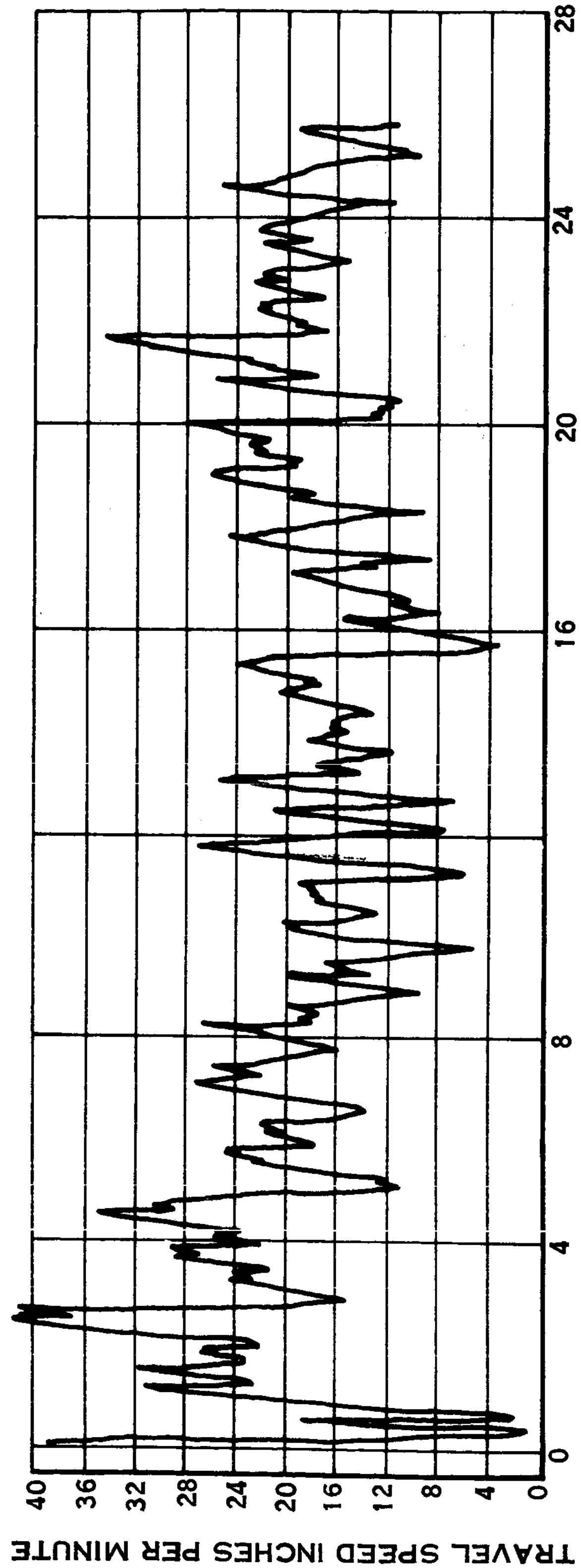


FIGURE 28 EXPERIMENTAL EVALUATION OF MANUAL SPEED CONTROL OF GUN TRAVEL

5.0 CONCLUSIONS

As a direct result of the design and development tests completed in this program, specific conclusions and comments can be made which are applicable to the in-space hand-held electron beam welder. The conclusions are as follows:

1. Electron beam welding is well-suited for producing in-space fusion welds.
2. The electron beam welding gun has been reduced significantly in size and sufficiently developed for use of this welder in a space environment.
3. Excellent portability has been achieved with the electron beam welder so as to warrant its use for in-space fabrication operations.
4. Since electron beam welding exhibits high operating efficiency and requires a minimum of power to produce a fusion weld of high quality, it appears that adequate power from the space vehicle is available for electron beam welding.
5. The design of the hand-held gun is sound, as verified by components and assembly development tests.
6. The prototype hand-held welder can be satisfactorily operated at the rated output power of 1.5 KW at 15 KV and 100 mA, or 20 KV and 75 mA.
7. The weld penetration capabilility of a 1.5 KW electron beam welder operating at 15 KV is adequate to fusion weld essentially all of the predicted weld applications intended for use in space.
8. Typical aerospace materials such as aluminum, titanium, and stainless steel can be welded successfully.
9. Satisfactory butt welds can be made in titanium and stainless steel in material thicknesses up to 0.125-inch for a welding speed of 15 ipm.
10. The welds are reproducible.
11. The complete gun assembly was used successfully by a space-suited technician to weld sample stainless steel weldments under a simulated space vacuum environment.
12. The vapor-radiation shield operated and functioned satisfactorily in eliminating material splatter, electrostatic charging, and radiation from the workpiece.
13. Reliable performance has been obtained from the power supply, interconnecting cable assembly, controls, and the electron beam gun.
14. There do not appear to be any state-of-the-art problems which would limit the use and evaluation of the prototype system for an in-space test, although additional technical investigation and development of human engineering work-handling techniques are required.

6.0 RECOMMENDATIONS

The following recommendations are made, based on the work accomplished under this program.

1. Basic programs are needed as follows:

   a. Additional man-rated chamber tests to determine and define the human engineering problems that may be associated with manual welding operations in a space-simulated vacuum environment.
   b. Adapting ancillary miniature devices to the hand-held gun to provide a more uniform welding speed and also a greater degree of accuracy for following a weld seam.
   c. A modified hand-held electron beam gun should be evaluated in a 6° zero-gravity simulator for the purpose of supplementing the man-rated chamber tests and also determining the manipulating problems that may be encountered during a zero-gravity in-space welding operation.

2. A light-weight high-density low-volume power supply should be matched and developed to the hand-held gun described in this report.

3. Conduct an in-space evaluation of electron beam welding techniques; these evaluations should be conducted by the astronaut manually operating the equipment.